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High Reliability Megawatt Transformer/Rectifier

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FOREWORD

This report covers research performed by Hughes Aircraft Company, Technology Support Division, Electro-Optical & Data Systems Group, El Segundo, California 90245, on Contract NAS3-25801, "High Reliability Megawatt Transformer/Rectifier." The period of research covered was from September 1989 to October 1990.

The research was performed by Samuel Zwass and Harry Ashe and the program manager was John W. Peters. The technical contributions of Dr. Ronald Robson (Hughes Research Laboratories) who designed the fault control circuitry of the DC to DC converter are gratefully acknowledged. The effort was sponsored by the Strategic Defense Initiative Office, Washington, D.C., and the project was managed by Dr. Ira T. Myers, NASA Lewis Research Center, Cleveland, Ohio.

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HIGH RELIABILITY MEGAWATT LEVEL TRANSFORMER/RECTIFIER TECHNOLOGY DEVELOPMENT PROGRAM

1.0 SUMMARY

The goal of the two phase program is to develop the technology and design and fabricate ultralightweight high reliability DC to DC converters for space power application. The converters will operate from a 5000 V dc source and deliver 1 MW of power at 100 kV dc. The power weight density goal is 0.1 kg/kW. The cycle to cycle voltage stability goal was ±1 percent RMS. The converter is to operate at an ambient temperature of -40°C with 16 minute power pulses and one hour off time.

The uniqueness of our Phase I design approach resides in the dc switching array which operates the converter at 20 kHz using unique Hollotron plasma switches along with a specially designed low loss, low leakage inductance and a lightweight high voltage transformer. This approach reduced considerably the number of components in the converter thereby increasing the system reliability. To achieve an optimum transformer for this application, the design uses four 25 kV secondary windings to produce the 100 kV dc output, thus reducing the transformer leakage inductance, and the ac voltage stresses. A specially designed insulation system improves the high voltage dielectric withstanding ability and reduces the insulation path thickness thereby reducing the component weight. Tradeoff studies and tests conducted on scaled-down model circuits and using representative coil insulation paths have verified the calculated transformer wave shape parameters and the insulation system safety.

In Phase I of the program a converter design approach was developed and a preliminary transformer design was completed. A fault control circuit was designed and a thermal profile of the converter was also developed. The converter design exceeds all the program goals including the following: less than 1 percent cycle to cycle voltage stability, a power weight density of 0.095 kg/kW and a fault tolerance energy of less than 50 joules.

For Phase II of the program in the first year a 50 kW breadboard converter will be fabricated and tested. The converter will include Hollotron switches that are capable of switching 10 A at 5000 V with less than 20 V forward drop, but will be packaged into 1 MW full size switch envelopes to aid in converter packaging development. The transformer and rectifiers will also be full voltage and power size. During the second year of Phase II all the full megawatt size components will be developed, fabricated and tested. The development of the full MW size Hollotron switches will also be started during the second year as well as the packaging design. During the third year of the Phase II program full 1 MW power switches will be fabricated, and 2 brassboard converters fully integrated and packaged into oil filled enclosures will be tested and delivered.

2.0 INTRODUCTION

Future space-based high power systems require advanced dc to dc converter technologies to achieve megawatt power levels ≤0.1 kg/kW specific mass, operating from -40°C up to 200°C. The overall objective of the two phase program is to design and demonstrate technology for a megawatt dc to dc converter in Phase I and to fabricate, test and deliver brassboard units during Phase II. This final report covers the design of a lightweight 1 MW transformer/ rectifier unit conducted at the Electro-Optical and Data Systems Group.

The dc to dc converter is designed to operate with input voltages of 5000 V dc and output voltages of 100 kV dc with cycle to cycle voltage stability of ±1.0 percent rms. The output is compatible with a dc resistive load and the converter system is designed to handle a fault tolerance energy of approximately 50 joules. The design of the overall megawatt dc to dc converter system consisting of the integrated T/R unit, the Hollotron plasma switches (Hughes Research Laboratories), and the filtering and fault protection circuitry has a specific weight less than 0.1 kg/kW.

The final report summarizes the three tasks completed under Phase I: 1) the design of the T/R unit, 2) the tradeoff studies and 3) the Phase II work plan. The Phase II program has been structured in three major tasks to be conducted in three consecutive years. In the first year a 50 kW breadboard dc to dc converter will be demonstrated; in the second year 1 MW Hollotron switches will be developed and 1 MW T/R components fabricated in parallel with development of a 1 MW package; in the third year two (2) 1 MW brassboard dc to dc converters will be fabricated, packaged and tested.

3.0 RESULTS AND DISCUSSION

The Phase I Megawatt Transformer/Rectifier Development Program consisted of three tasks: 1) a preliminary design study, 2) tradeoff studies and 3) Phase II work plan. The results of these three tasks are presented in Sections 3.0, 4.0, and 5.0.

3.1 PRELIMINARY TRANSFORMER DESIGN SUMMARY

A 1 MW transformer/rectifier (T/R) unit has been designed to operate from a 5 kV dc supply switched at 20 kHz with a weight which is compatible with an overall specific weight of 0.1 kg/kW for the entire dc to dc converter system shown in Figure 1. The T/R will step up the voltage to 100 kV dc with greater than 99.3 percent efficiency.

After conducting extensive trade-off studies on the transformer characteristics, frequency response, voltage stress, weight and thermal analysis, the final optimized transformer design was established as shown in Figures 2 through 9.

Figure 2 shows the schematic diagram of the transformer showing a centertap primary and four secondary windings.

Figure 3 gives the outline dimensions of the transformer showing the leads breakout, the wound in cooling rods and the core banding.

The winding details for coil I and coil II are given in Figures 4 and 5 respectively. They show that each coil consists of 3 primary sections with secondary windings interleaved between them. Each primary section is a centertapped winding having two AWG No. 14 gage windings connected in parallel. The insulation pads between the primaries and secondaries increase in thickness corresponding to the secondary bias voltages developed. Figure 6 shows the coils cross section and details of the winding and insulation construction. The insulation consists of interleaved unimpregnated glass cloth and H-film buildup to pad thicknesses indicated in the winding instructions.

Figure 7 shows the in-process transformer parameters tests such as inductance, core loss, DCR, turns ratio, leakage inductance as well as pulse parameters tests and high voltage corona tests.

The transformer is designed as a 2-coil construction using a 0.0025 cm thick HYMU nickel C-core of size shown in Figure 8. For good heat conduction the coils are wound on an aluminum alloy winding form shown in Figure 9.

As the transformer operates at a flux density of 5 kilogauss, the core is specified (see Figure 8) to be heat treated for lowest losses at the 5 kilogauss 20 kilohertz level.

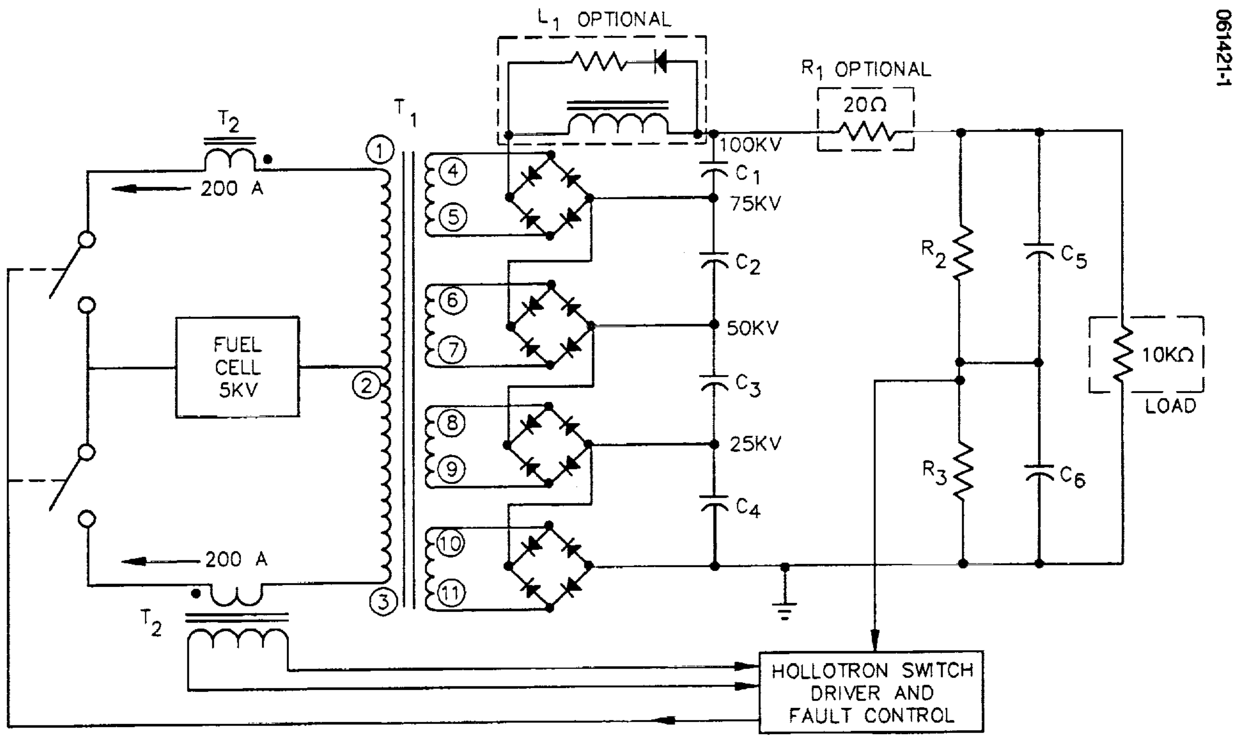


Figure 1. 1 MW DC to DC converter basic schematic and fault control.

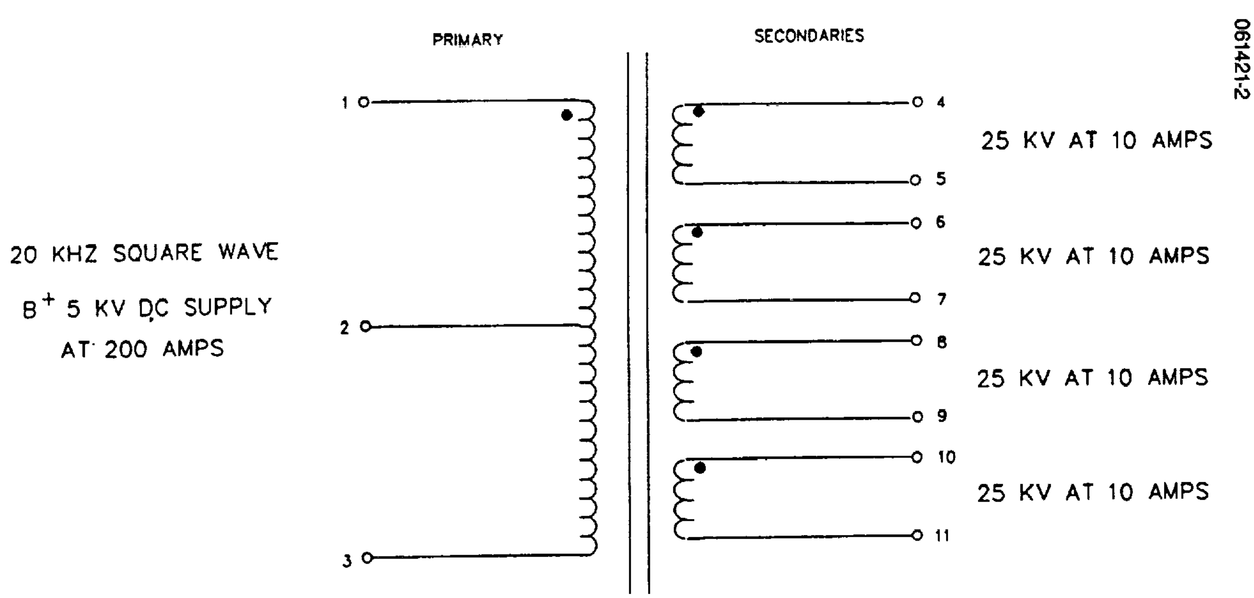
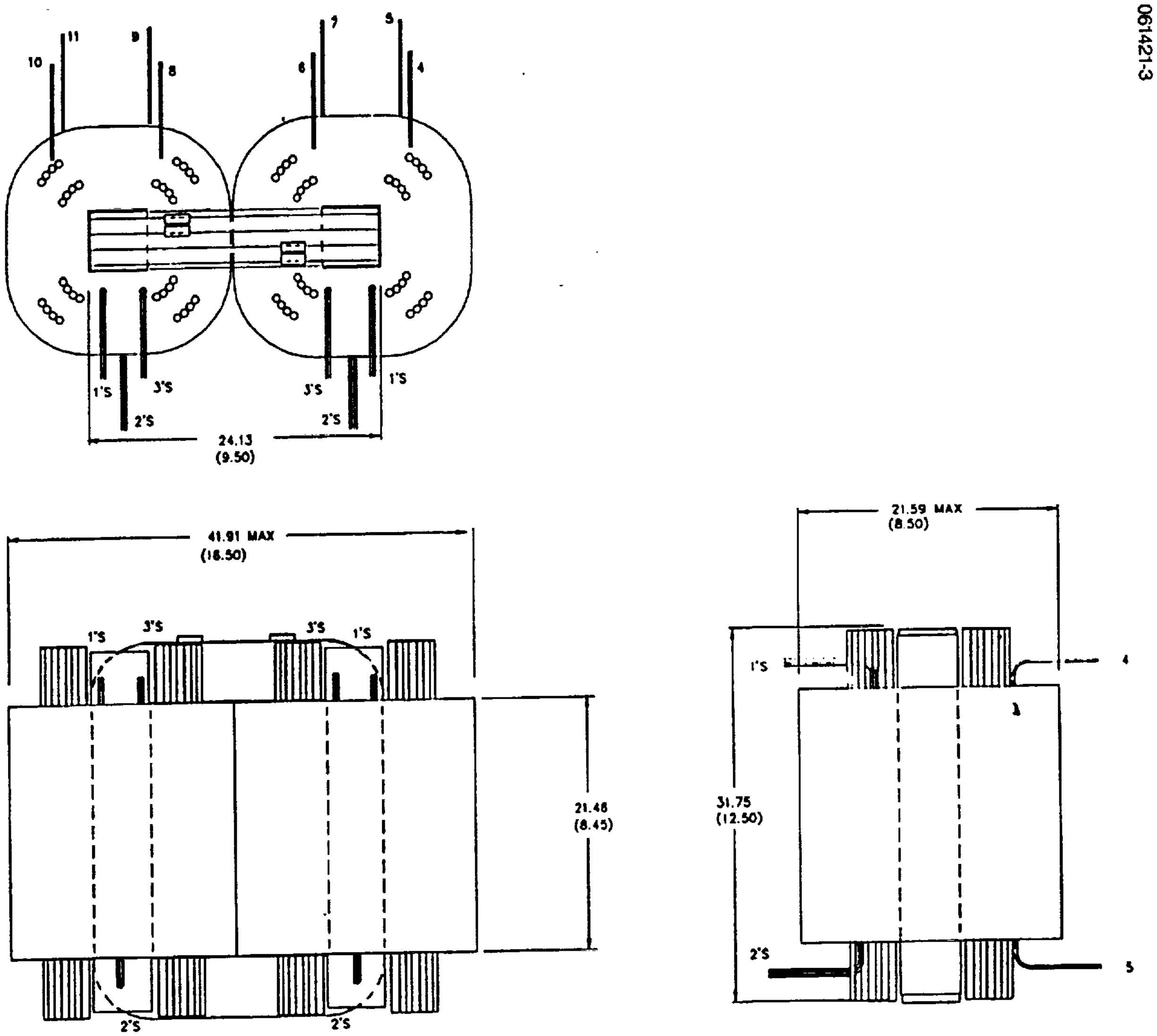


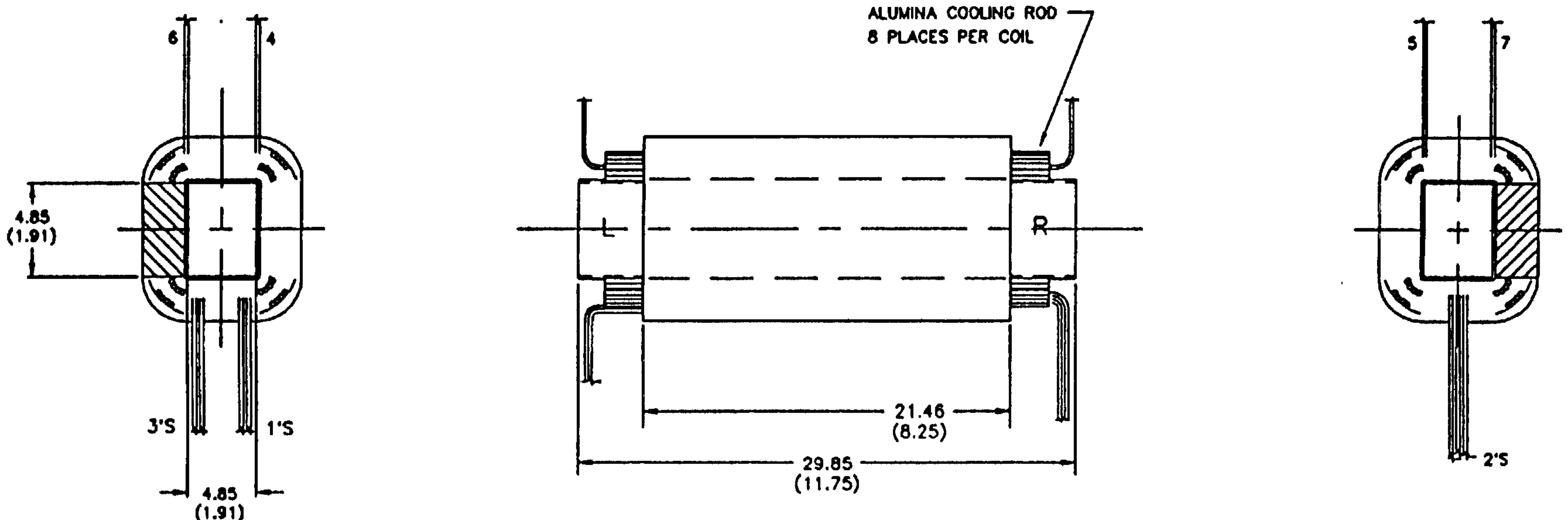
Figure 2. Transformer schematic diagram.



1. DIMENSIONS ARE IN CENTIMETERS (INCHES)

NOTES:

Figure 3. Transformer assembly.

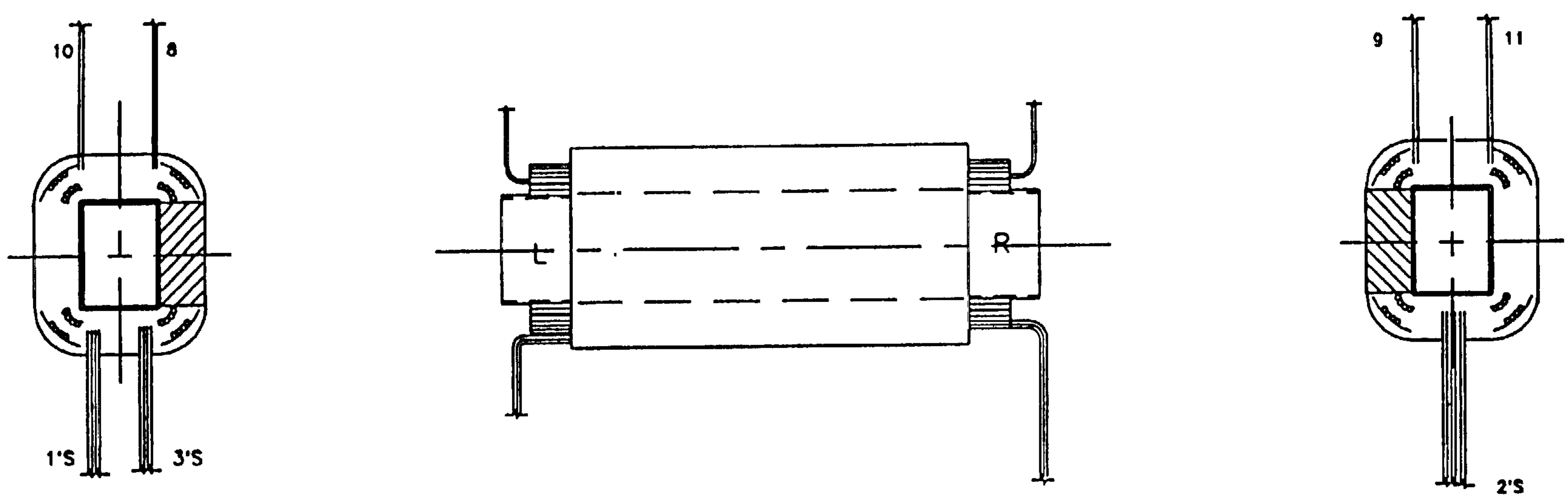


WINDING DATA

WINDING COIL I	1–2	1–2	2–3	2–3	4 – 5	1–2	1–2	2–3	2–3	6 – 7	1–2	1–2	2–3	2–3
WIRE SIZE (ALUMINUM)	NO. 14 HML		NO. 14 HML		NO. 15 HML	NO. 14 HML		NO. 14 HML		NO. 15 HML	NO. 14 HML		NO. 14 HML	
WINDING LENGTH, EACH LAYER	12.40 (4.90)		12.40 (4.90)		11.17 (4.40)	12.40 (4.90)		12.40 (4.90)		11.17 (4.40)	12.40 (4.90)		12.40 (4.90)	
START AT	L		R		L	L		R		L	L		R	
NUMBER OF LAYERS	1	1	1	1	5	1	1	1	1	5	1	1	1	1
TURNS PER LAYER	63	63	63	63	66	63	63	63	63	66	63	63	63	63
TOTAL TURNS, ±0	63	63	63	63	330	63	63	63	63	330	63	63	63	63
LAYER INSULATION	—		—		.076 (.030) 2	—		—		.076 (.030) 2	—		—	
WRAPPER 2	0.03 (.010)	0.05 (.020)	0.03 (.010)	0.18 (.070)	0.18 (.070)	0.03 (.010)	0.05 (.020)	0.03 (.010)	0.38 (.150)	0.38 (.150)	0.03 (.010)	0.05 (.020)	0.03 (.010)	0.05 (.020)
DC RESISTANCE (OHMS)	.095		.106		1.75	.155		.168		2.6	.225		.240	

NOTES:
1. DIMENSIONS ARE IN CENTIMETERS (INCHES)
2. HML = 220°C HEAVY (DOUBLE) POLIMIDE COATED WIRE (FED. SPEC. J-W-1177/15)

Figure 4. Coil I.



WINDING DATA

WINDING COIL II	3-2	3-2	2-1	2-1	9 - 8	3-2	3-2	2-1	2-1	11 - 10	3-2	3-2	2-1	2-1
WIRE SIZE (ALUMINUM)	NO. 14 HML		NO. 14 HML		NO. 15 HML	NO. 14 HML		NO. 14 HML		NO. 15 HML	NO. 14 HML		NO. 14 HML	
WINDING LENGTH, EACH LAYER	12.40 (4.90)		12.40 (4.90)		11.17 (4.40)	12.40 (4.90)		12.40 (4.90)		11.17 (4.40)	12.40 (4.90)		12.40 (4.90)	
START AT	L		R		L	L		R		L	L		R	
NUMBER OF LAYERS	1	1	1	1	5	1	1	1	1	5	1	1	1	1
TURNS PER LAYER	63	63	63	63	66	63	63	63	63	66	63	63	63	63
TOTAL TURNS, ±0	63	63	63	63	330	63	63	63	63	330	63	63	63	63
LAYER INSULATION	—		—		.076 (.030) 2	—		—		.076 (.030) 2	—		—	
WRAPPER 2	0.03 (.010)	0.05 (.020)	0.03 (.010)	0.58 (.230)	0.58 (.230)	0.03 (.010)	0.05 (.020)	0.03 (.010)	0.84 (.330)	0.84 (.330)	0.03 (.010)	0.05 (.020)	0.03 (.010)	0.05 (.020)
DC RESISTANCE (OHMS)	.095		.106		1.9	.18		.19		3.06	.28		.29	

2. HML = 220° HEAVY (DOUBLE) COATED POLYIMIDE WIRE (FED SPEC J-W-1177/15)
1. DIMENSIONS ARE IN CENTIMETERS (INCHES)
NOTE:

Figure 5. Coil II.

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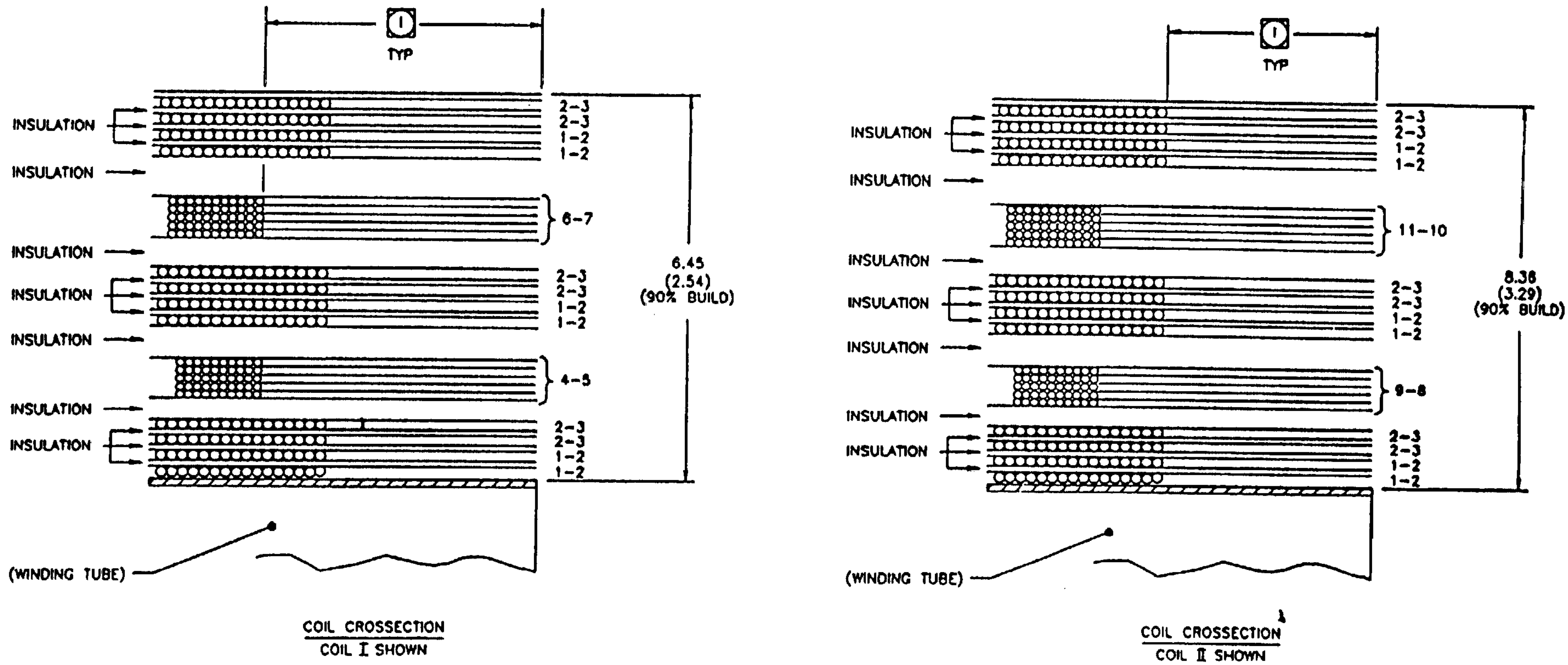


6. DIMENSIONS ARE IN CENTIMETERS (INCHES)

5. BRING LEADS OUT APPROX. AS SHOWN AND KEEP EQUAL MARGINS.

4. ANCHOR WINDINGS MECHANICALLY, USING "BEN HAR" SLEEVING. USE NO ADHESIVES.

3. ALL START AND FINISH LEADS TO BE SELF, 20.32 cm (8 INCHES) LONG, TRIPLE SLEEVED WITH "BEN HAR" UNIMPREGNATED GLASS SLEEVING.

2 ALL INSULATION CONSISTS OF 1 LAYER OF 0.0076 cm (.003 IN) UNIMPREGNATED GLASS CLOTH, AND 1 LAYER OF 0.0076 cm (.003 IN) H-FILM INTERLEAVED. NUMBER OF WRAPS AS REQUIRED TO BUILD UP TO SPECIFIED HEIGHT.

1 BUILD UP MARGINS USING THE ABOVE INSULATION AS REQUIRED TO MATCH WIRE LAYER THICKNESS.

NOTES -- UNLESS OTHERWISE SPECIFIED

Figure 6. Coil cross section and winding/insulation construction.

061421-7

1. INDUCTANCE AND CORE LOSS:
   APPLY 5550 VRMS AT 20 KHZ (SINE) TO 1-2
   $L \leq 40$ mH, CORE LOSS ≤ 1000 WATTS
   ALTERNATE TEST IF BUILT TO THIS DESIGN:
   APPLY 555 VRMS AT 2KHZ TO 1-2
   $L \leq 40$ mH, CORE LOSS ≤ 35 W

2. TURNS RATIO: at 1.0 V rms , 10 Khz
   1-2/4-5 = 1-2/6-7 = 1-2/8-9 = 1-2/10-11 = 63/330 + 2%
   1-2/1-3 = 1/2 ± 1%

3. DC RESISTANCE: ± 10%
   1-2 , 2-3 = .03 OHMS
   4-5 , 6-7 , 8-9 , 10-11 —Winding
   1.71 , 2.57, 1.86, 3.04 —Ohms

4. LEAKAGE INDUCTANCE AND SRF: $L_{1-2} = L_{2-3}$, $SRF_{1-2} = SRF_{2-3}$

SHORT 4-5 – MEASURE L_{1-2} AND SRF_{1-2}	≤ 50 uH ,	≥ 100 Khz.
SHORT 6-7 – MEASURE L_{1-2} AND SRF_{1-2}	≤ 75 uH ,	≥ 80 Khz
SHORT 8-9 – MEASURE L_{1-2} AND SRF_{1-2}	≤ 100 uH ,	≥ 70 Khz
SHORT 10-11 – MEASURE L_{1-2} AND SRF_{1-2}	≤ 120 uH ,	≥ 60 Khz

   REPEAT ABOVE TEST BUT MEASURE L_{2-3} AND SRF_{2-3} FOR EACH SHORT

5. CORONA INCEPTION (IN FREON): At 50 KV DC ± 12.5 KV rms from each secondary to primary and core.

6. RISE AND FALL TIMES, AND DROP OF EACH SECONDARY USING LOW LEVEL SQUARE WAVE SOURCE AS SHOWN BELOW: $t_R = t_F \leq 2.0$ microseconds , Droop $\leq 5\%$

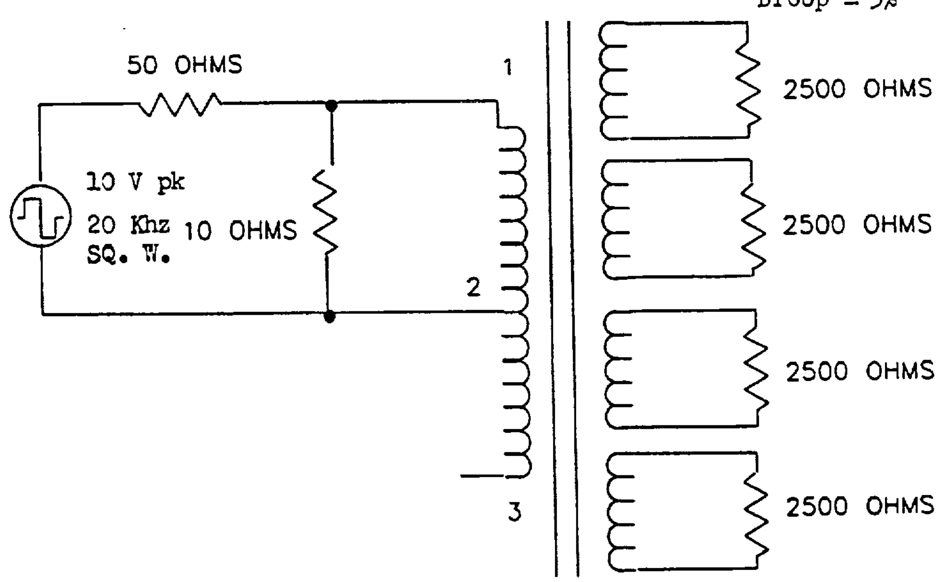
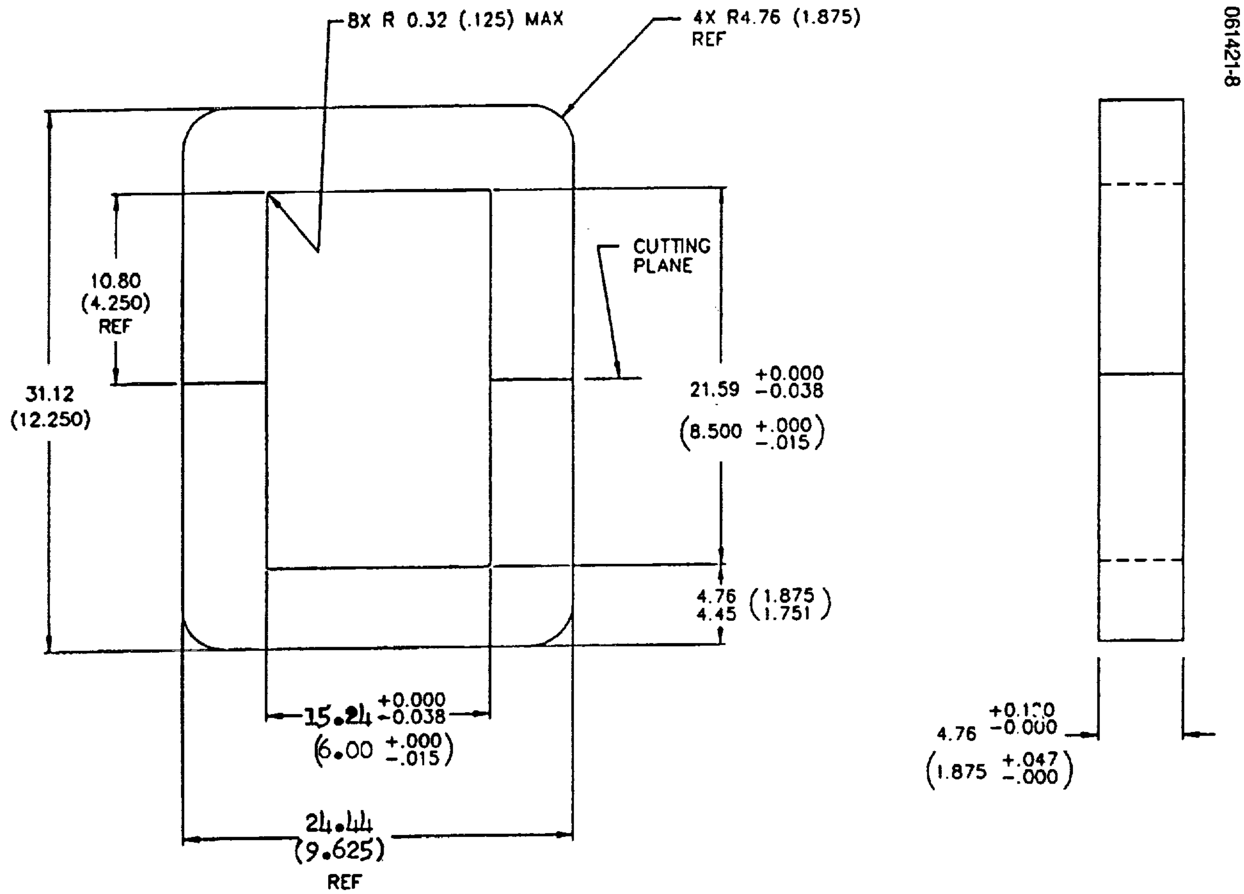


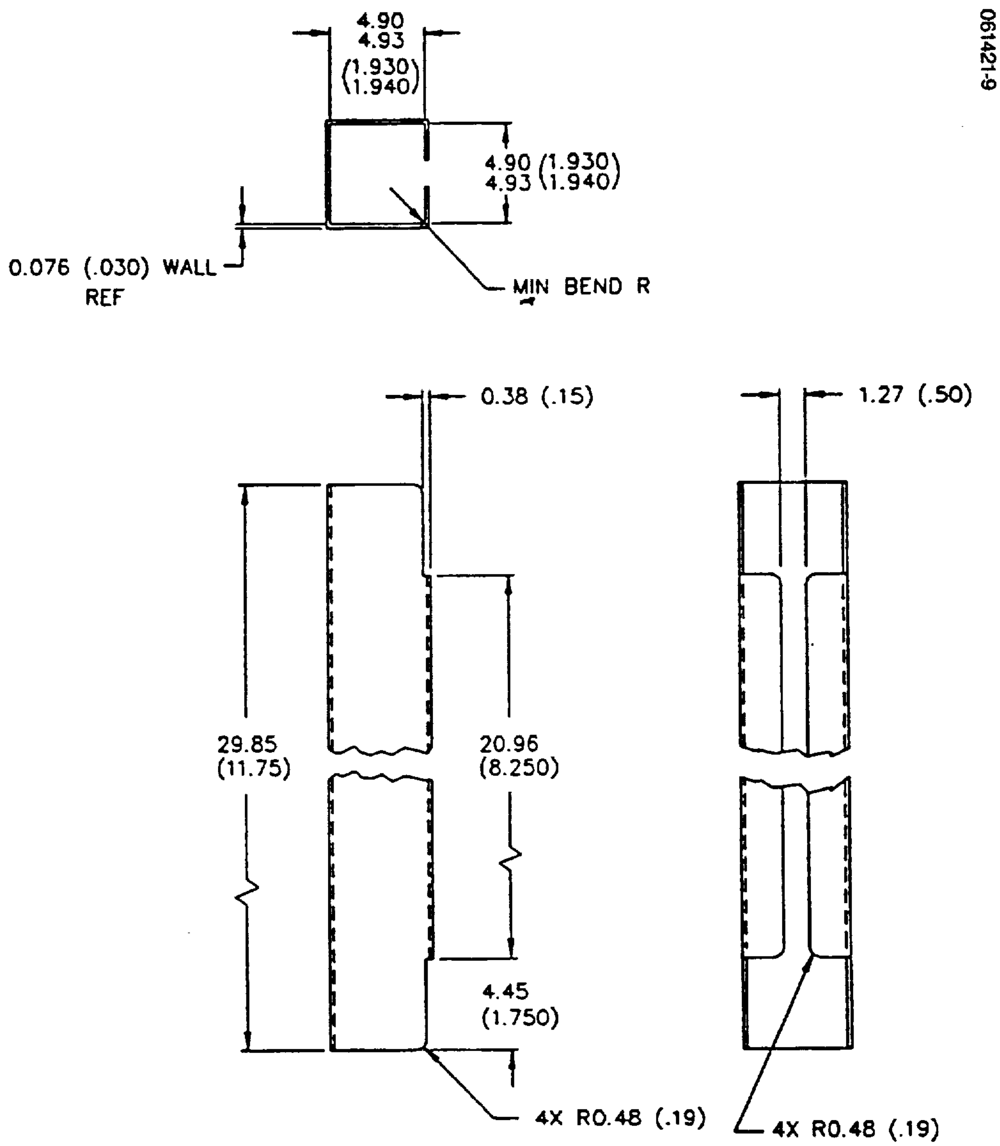
Figure 7. Acceptance tests.



4. DIMENSIONS ARE IN CENTIMETERS (INCHES)
3. HEAT TREAT AND ANNEAL FOR LOWEST LOSSES FOR 20kHz SQUARE WAVE AND 5 KILOGAUSS
2. 1 REQUIRED PER UNIT
1. MATL: .0025 cm (.001 IN) HYMU C-CORE OR EQUIVALENT

NOTES:

Figure 8. Core.



6. DIMENSIONS ARE IN CENTIMETERS (INCHES)
5. 2 REQUIRED PER UNIT
4. ANODIZE PER MIL-A-8625, TYPE III, CL 1,
   0.005 ±0.001 cm (.002 ± .0005 INCH) THICK
3. DIMENSIONS APPLY AFTER ANODIZING
2. REMOVE BURRS AND BREAK SHARP EDGES APPROX R.010
1. MATL: .040 SHEET, AL ALLOY 2024-0,
   QQ-A-250/4, TEMPER 0

NOTES:

Figure 9. Winding tube.

3.2 SCALED DOWN BENCH MODEL TEST CIRCUIT

To verify the transformer operating characteristics in a 20 kHz inverter circuit, a 100 to 1 voltage scaled down transformer and switching circuit shown in Figure 10 was designed and built. The transformer maintained the two coil construction with the same turns ratio, interleaving and spacing as the full scale transformer design.

Measurements of all parameters including primary inductance, ratio, dc resistances, leakage inductance and self resonant frequency were performed to verify the calculated parameter values.

The test circuit utilized power hexfets as switches and full wave bridge rectifiers at the secondaries. A 20 K ohm load at the output developed 50 watts at 1020 volts, which was the calculated output expected. Waveshapes, rise and fall times, ringing and droop were photographed and documented in Figures 11 and 12.

In addition a pulse width modulated driver was constructed to drive the hexfets and transformer. P.W.M. operation including a programmed dead-time was observed and documented.

The results of the tests performed indicates that the design calculations are very close to the actual transformer test results. This reinforced our confidence that the full scale T/R unit will also meet the parameter limits calculated and thus will operate satisfactorily in the expected application.

The calculated leakage inductance of 6.1 μH compares very favorably with the 7.0 μH measured result. The measured turns ratio, dc resistances, core loss, winding capacitances and self resonance frequency agreed closely with the design calculations.

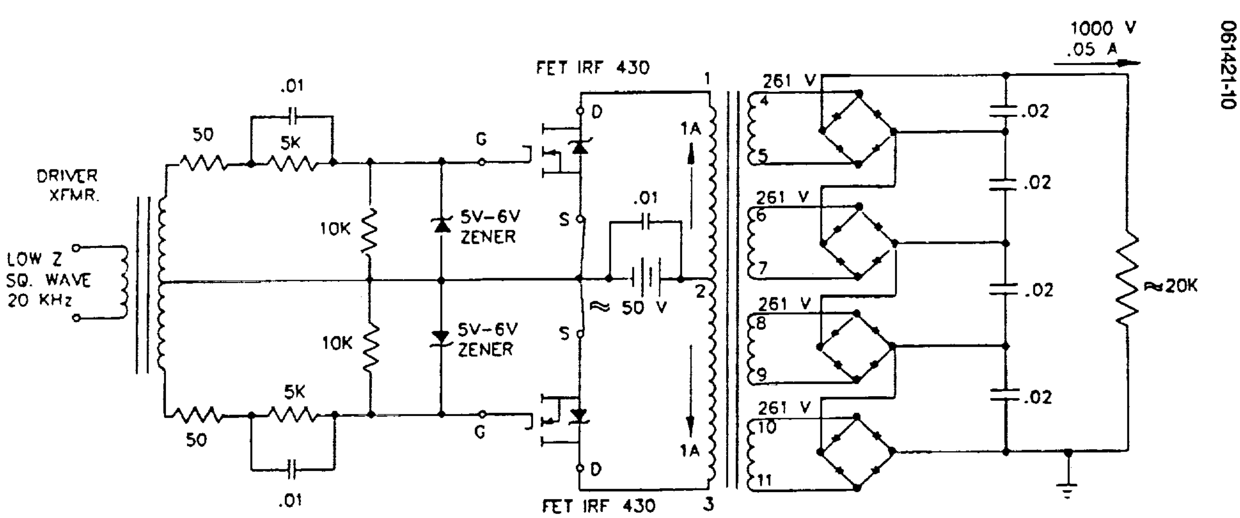
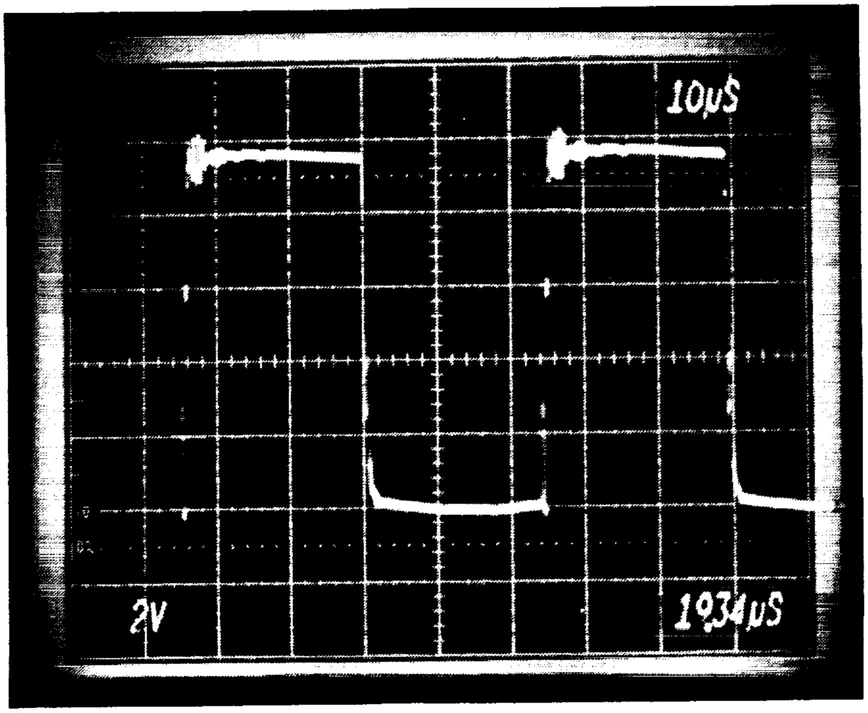


Figure 10. Bench model 20 kHz inverter circuit voltage scaled 100:1.



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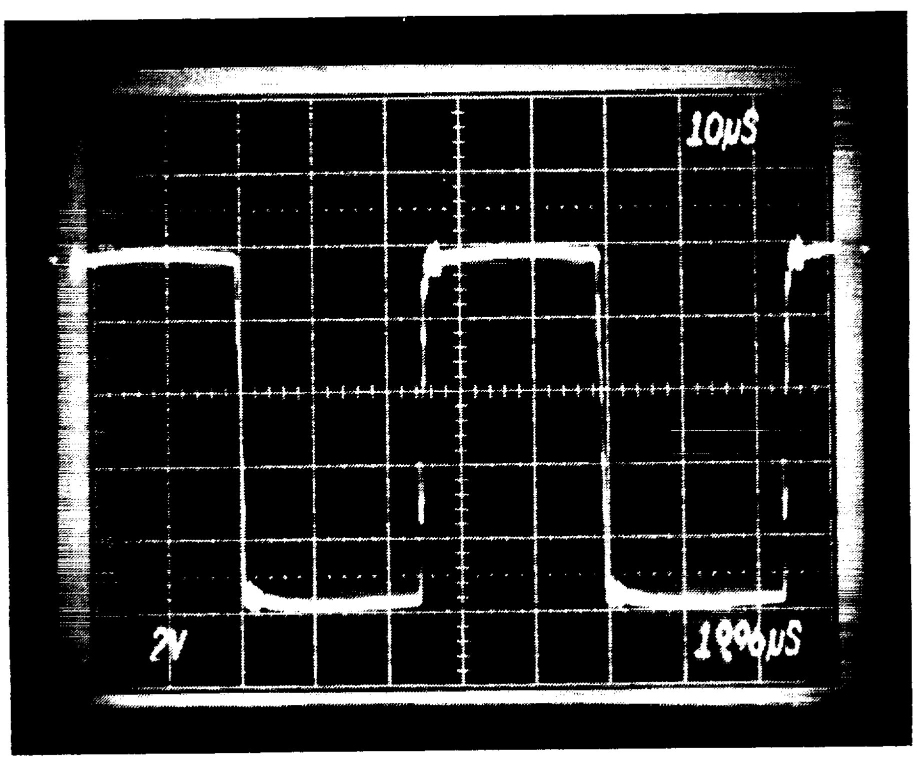
- RISE TIME ~ 1 µSEC
- OVERSHOOT ~ 5%
- DROOP ~ 1%
- NO CURRENT SHUT-OFF SPIKES
- FALL TIME ~ 1 µSEC
- NO BACKSWING

Figure 11. 20 kHz waveform across FET switch bench model circuit.



061421-12

- RISE TIIME < 1 µSEC
- < 5% OVERSHOOT
- < 1% DROOP
- FALL TIME ~ 1 µSEC
- NO BACKSWING

Figure 12. 20 kHz waveform at primary coil bench model circuit.

The measured wave shapes are very close to or better than the calculated values: Test results, of the actual switching circuit at 20 kHz square wave, 50 volts dc input and 1000 V dc output into a 20 K ohms load, show a rise time of about 0.8 μsec, an overshoot of less than 5 percent, and a droop of about 1 percent with no backswing or noticeable current spikes across the switches or transformer primary. Driving the switches with a pulse width modulated driver to add a "dead" time to the square wave did not affect the pulse shape parameters. This is very encouraging as it does not add voltage stresses and losses to the switches or T/R system.

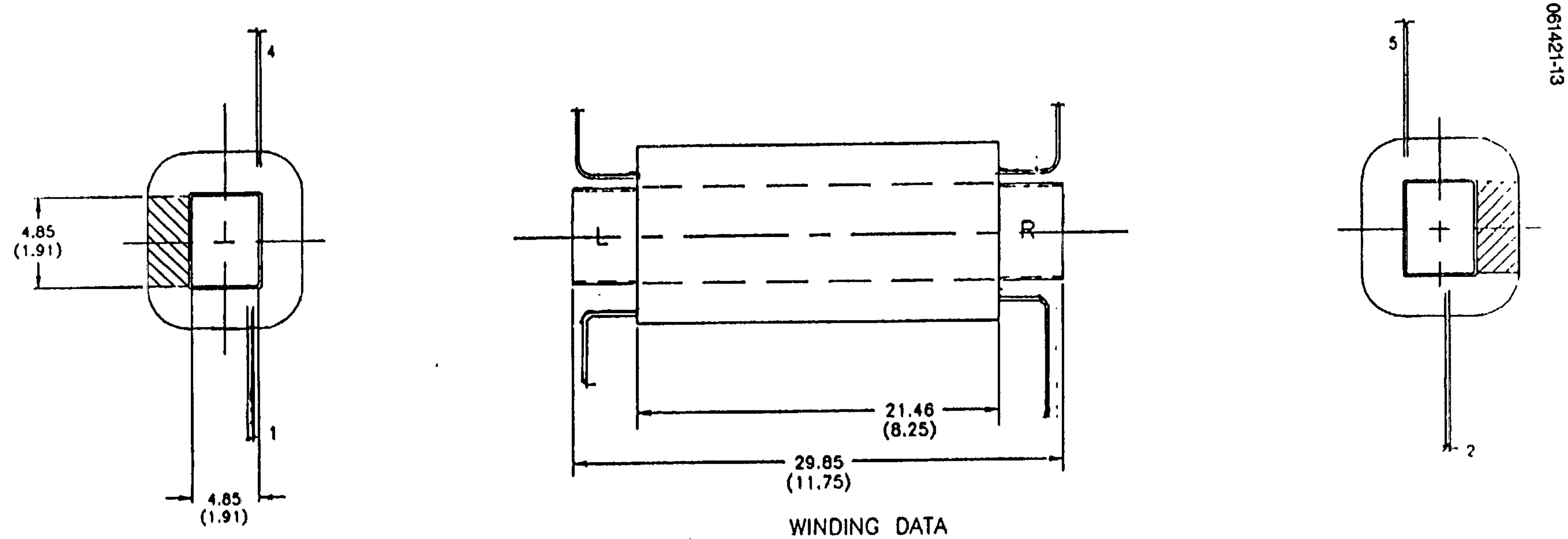
3.3 EXPERIMENTAL TEST COIL

To evaluate the design voltage stress limits of the insulation system used and its effect on the reliability of the transformers a test coil shown in Figures 13 and 14 was fabricated and tested. The test coil reflected the actual size, insulation system, pad thickness and wire gages of one secondary winding interleaved between two primary winding layers.

The first experimental test coil was wound on a 0.63 mm thick fiberglass rectangular tube with inside dimensions of 4.3 cm x 5.3 cm and a length of 21.5 cm. The windings consisted of one layer AWG No. 14 copper magnet wire centered on the winding form occupying a winding length of 14 cm; the wrapper over the first primary winding layer consisted of 0.076 mm fiberglass cloth built up to a pad thickness of 3.8 mm. The one layer secondary winding consisted of AWG No. 15 copper magnet wire with an 11.7 cm winding length centered over the primary layer insulation. The secondary winding was also wrapped with a 3.8 mm thick fiberglass cloth pad. Then another primary winding layer was placed over it similar to the first primary. Thus a secondary winding interleaved between two primary windings was achieved, with insulation spacing similar to the first secondary of the actual preliminary design coil. The primary leads were connected together and terminated to a 1 cm corona ball representing one test electrode. The secondary leads brought out diagonally on the other side of the coil were also terminated to a 1 cm corona ball providing the second test electrode. The test coil was vacuum impregnated in silicate ester fluid and placed in the Biddle corona test equipment. The dc voltage across the test coil electrodes was gradually raised. At just above the 65 kV dc level an arc occurred between the secondary and the outer primary winding.

The coil was rewound identically to the first test coil except the insulation pads between the secondary and the primaries were changed (see Coil No. 2 drawings Figure 13 and 14). The new insulation consisted of 1 layer of 0.076 mm H-film in between the 2 cloth layers, built up to a pad thickness of 5.25 mm. This test coil represented the spacing of the second secondary coil of the actual transformer design. To assure that a breakdown would not be caused by an incomplete oil impregnation, (which may have been the cause of breakdown of the first test coil), we impregnated this test coil in freon (oil is more difficult to impregnate into a coil than freon).

A high dc voltage was applied between the two parallel connected primaries and the secondary winding layer. At 115 kV dc an arc occurred in the margin of the secondary winding layer. After the arc, the coil was again able to hold off up to 115 kV dc at which level an arc in the margin occurred every 20 to 30 seconds. The test coil margin is about 3.8 centimeters (the final coil design margin is 5.1 centimeters). The test results of the experimental coils are summarized in Table 1.

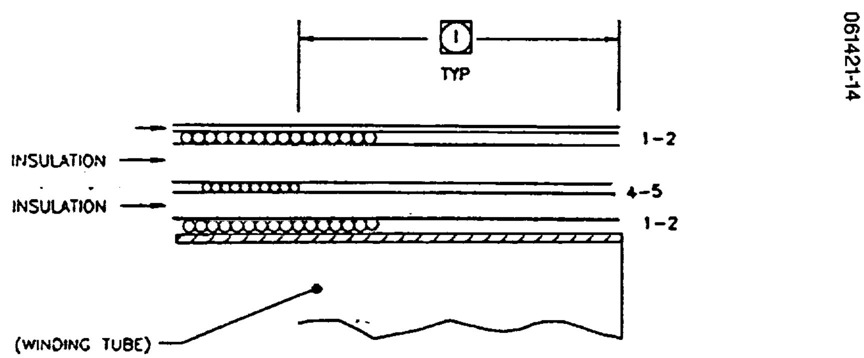


WINDING DATA

WINDING COIL I	1–2	4 – 5	1–2
WIRE SIZE (ALUMINUM)	NO. 14 HML	NO. 15 HML	NO. 14 HML
WINDING LENGTH, EACH LAYER	12.40 (4.90)	11.17 (4.40)	12.40 (4.90)
START AT	L	L	L
NUMBER OF LAYERS	1	1	1
TURNS PER LAYER	63	66	63
TOTAL TURNS, ±0	63	66	63
LAYER INSULATION	—	—	—
WRAPPER $\boxed{2}$	0.50 (.20)	0.50 (.20)	0.03 (.010)

2. HML = 220° HEAVY (DOUBLE) COATED POLYIMIDE WIRE (FED SPEC J-W-1177/15)
1. DIMENSIONS ARE IN CENTIMETERS (INCHES)
NOTE:

Figure 13. Test coil.



COIL CROSSECTION
COIL I SHOWN

6. DIMENSIONS ARE IN CENTIMETERS (INCHES)
5. BRING LEADS OUT APPROX. AS SHOWN AND KEEP EQUAL MARGINS.
4. ANCHOR WINDINGS MECHANICALLY, USING "BEN HAR" SLEEVING. USE NO ADHESIVES.
3. ALL START AND FINISH LEADS TO BE SELF, 20.32 cm (8 INCHES) LONG, TRIPLE SLEEVED WITH "BEN HAR" UNIMPREGNATED GLASS SLEEVING.

2 ALL INSULATION CONSISTS OF 2 LAYERS OF 0.0076 cm (.003 IN) UNIMPREGNATED GLASS CLOTH, AND 1 LAYER OF 0.0076 cm (.003 IN) H-FILM INTERLEAVED. NUMBER OF WRAPS AS REQUIRED TO BUILD UP TO SPECIFIED HEIGHT.

1 BUILD UP MARGINS USING THE ABOVE INSULATION AS REQUIRED TO MATCH WIRE LAYER THICKNESS.

NOTES -- UNLESS OTHERWISE SPECIFIED

Figure 14. Test coil crossection.

TABLE 1. TEST RESULTS

Test Coil	Insulation	Spacing cm	Design Operating Voltage	Test Voltage	Remarks
Coil 1	Glass cloth in silicate ester fluid	0.38	37.5 kV	65.0 kV dc	Arc between primary and secondary
Coil 2	Glass cloth and H-film in Freon	0.50	50.0 kV	1. 65 kV dc for 5 minutes	Passes
				2. 75 kV dc for 2 minutes	Passed
				3. 25 kV rms for 2 minutes	Passed
				4. 35 kV rms for 2 minutes	Passed
				5a. 52.5 kV dc plus 17.5 kV rms for 11 minutes	Passed (5a and 5b total 16 minutes continuous)
				5b. 60 kV dc plus 17.5 kV rms for 5 minutes more	
				6. Repeat tests 2 and 4	Passes
				7. 115 kV dc	Arc in the margin every 25 seconds

3.4 CONCLUSIONS

Based on the experimental test coil results we were able to confirm the suitability of the selected insulation system for the high voltage application, establish operating stress levels with adequate safety margins and finalize the transformer design.

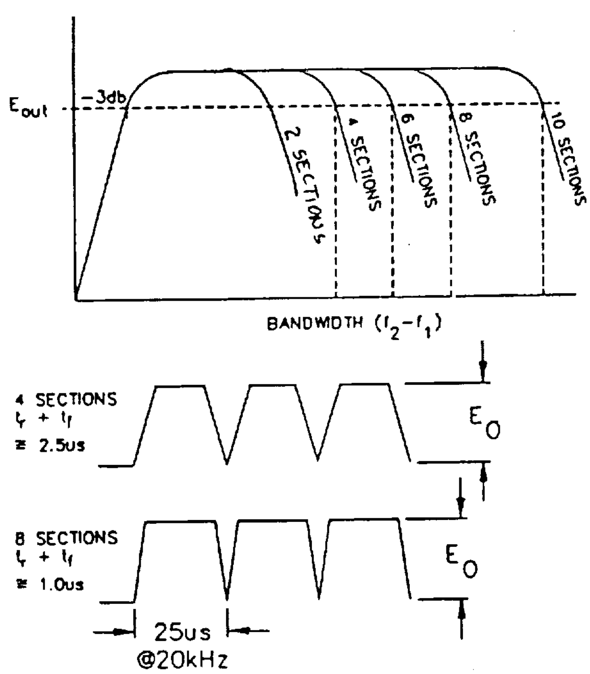
4.0 TRADEOFF STUDIES

Transformer frequency response, voltage stresses, rectifier selection, efficiency, weight optimization, thermal analyses, and reliability of the T/R unit are documented in this section.

4.1 TRANSFORMER FREQUENCY RESPONSE

To maintain the small size and weight of the transformer a high operating switching frequency is desired. Since the optimum switching frequency of the plasma switches is at about 20 kHz, the transformer was designed to operate at the 20 kHz frequency.

Tradeoff studies were conducted to develop a 20 kHz transformer design having a square wave response with minimum wave shape distortion. Taking into consideration the effect of the number of secondary windings on rise time and bandwidth response, high operating voltages, winding complexity, ripple, efficiency and transformer reliability, the selection of four secondary windings resulted in an optimum transformer design. The four secondary windings reduces the transformer turns ratio (thus limiting the ac voltage within the system to 25 kV), which in turn reduces the leakage inductance, ripple, and the required energy storage capacitor values. With only four secondary windings the transformers complexity is not increased appreciably thus maintaining high transformer reliability. Figure 15 lists advantages and disadvantages as a function of an increasing number of secondary sections. With four secondary sections each secondary delivers only 25 kV dc, and they are stacked up to achieve the required total output of 100 kV dc.



LARGER NUMBER OF SECONDARY SECTIONS

ADVANTAGES

- LARGER BANDWIDTH
- LESS RIPPLE/NARROWER NOTCHES
- MAX. AVERAGE VOLTAGE
- REDUCED CAPACITOR ENERGY STORAGE

DISADVANTAGES

- REDUCED RELIABILITY MORE H.V. TERMINATIONS
- COMPLEX WINDING CONFIGURATION

Figure 15. Transformer bandwidth optimization versus number of secondaries.

4.2 TRANSFORMER VOLTAGE STRESSES

The winding layout, terminations and the insulation systems were selected to result in safe peak operating voltage stresses. Results from the experimental test coils described in Section 3.3 were used to guide the final design of the transformer in the selection of the insulating system, winding configuration and spacing. Table 2 shows the spacing and the insulation pads thickness between the windings, and the resulting average and peak voltage stresses. The stresses that the test coils experienced when arcing was initiated are nearly twice the coil design operating stresses, clearly indicating the superiority of the insulation system with a high margin of safety.

TABLE 2. WINDING STRESS VERSUS SPACING

Windings	Operating Voltage in kV	Spacing in cm	Average Stress in kV/cm	Peak in kV/cm
Primary layer to layer	5	0.050	100.0	114.8
Secondary layer to layer	10	0.076	131.6	163.8
Primary to Section 1	25	0.180	138.9	213.8
Primary to Section 2	50	0.380	131.6	268.3
Primary to Section 3	75	0.580	129.3	368.7
Primary to Section 4	100	0.840	119.0	390.3

Test Coil	Nominal Voltage	Spacing in cm	Average Stress kV/cm Nominal/at Arc	Peak Stress Kv/cm nominal/at Arc
1	50	0.380	131.6/171.0	308.5/401.1
2	75	0.500	150.0/230.0	346.9/532.0

The arcing in test coil 1 occurred in a void at a stress level considerably higher than the operating level. Electrical stress on test coil 2 at the 115 kV level did not reach the insulation withstanding voltage limit. The arcing was along the shortened creepage path caused by stray fiber strands building up charges at their tips. The final transformer insulation material will, in addition to larger margins, use glass cloth with woven in edges to eliminate fiber strands at the edges. It should be noted that the transformer design operating stress voltages are well within safe operating limits, and tests indicate the dielectric withstanding limit capability of the insulation system to be several times greater than the operating voltage stresses. Also in addition to an increase in spacing, the use of an interleaved insulation with Kapton film provides a solid insulation barrier considerably increasing the insulation's dielectric withstanding voltage and the transformer reliability.

4.3 VOLTAGE RECTIFICATION

To avoid high ac voltages the transformer secondaries generate only 25 kV ac in each of the four secondary windings. The output of each secondary is full wave bridge rectified using four high voltage fast recovery rectifier stacks for an output of 25 kV dc. The four 25 kV dc secondary outputs are stacked up to deliver the required 100 kV dc output to the load. This system avoids exposing the insulation to a high (100 kV) ac voltage stress, and only exposes some components to the 100 kV dc, a considerable less stressful condition than an equal ac stress level.

Each rectifier column stack consists of 40 series connected 1 kV peak inverse voltage fast recovery diodes. The column construction minimizes corona effects by using rounded corona shields held at intermediate potentials by a voltage dividing network, which connects all metallic parts eliminating the possibility of partial breakdown. The highest gradient in open space is held to below 1200 volts per millimeter. Each rectifier column arm shown in Figure 16 weighs 1.4 kg and is 27.4 cm long x 5.3 cm high x 9.7 cm wide. Four columns comprise one full wave rectifier bridge. The four bridges (16 columns) weight a total of 23 kg. The diode losses run about 200W per column bringing the total rectifier losses to about 3200 watts.

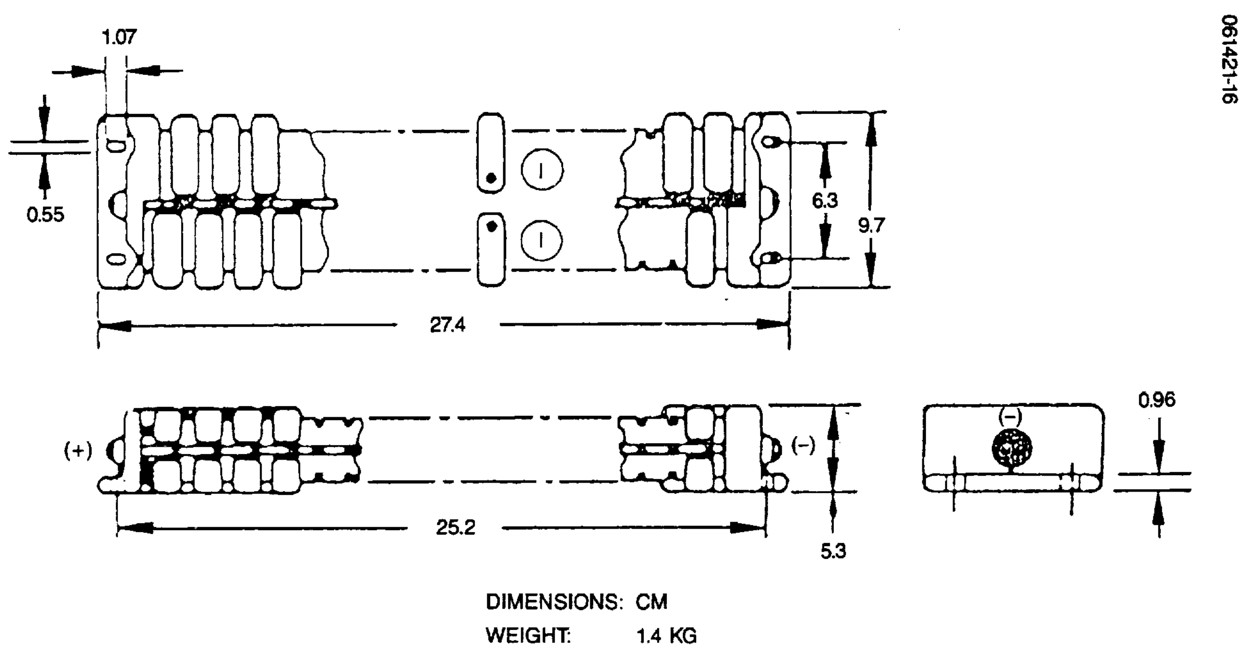


Figure 16. 40 kV rectifier arm.

4.4 EFFICIENCY AND WEIGHT

To achieve high efficiency, the transformer and all other losses are kept to a minimum. Therefore, the core is designed to operate at a flux density of 5 k gauss using 0.025 mm thick nickel core material resulting in low core losses and a low number of winding turns. By keeping the insulation pad thickness to a minimum, consistent with safe voltage stresses, the winding mean length turn is also minimized and so are the winding dc resistances. The high core flux level and small insulation pad thickness also keep the coil build up, the core and coil size and the weight to a minimum.

In order to further reduce the transformer weight aluminum wire instead of copper is used for the windings.

4.4.1 Skin Effect

The winding ac resistances at the 20 kHz operating frequency are higher than the calculated dc resistances due to the proximity and skin effect. The "skin" depth of the current in a conductor as a function of frequency can be calculated from the following formula:

$$\Delta = \left(\frac{1}{\pi f \mu \delta}\right)^{1/2}$$

where

- Δ is skin depth in meters
- μ permeability = $\mu_0 = 4\pi\ 10^{-7}$
- f frequency in Hz
- δ conductivity in mhos per meter

for the aluminum wire $\Delta = 0.05976$ cm.

The ac to dc resistance ratio is

$$\frac{R_{AC}}{R_{DC}} = \frac{1}{2\left(\frac{\Delta}{r}\right) - \left(\frac{\Delta}{r}\right)^2}$$

where r is the conductor radius in centimeters, and Δ is the skin depth in cm.

The ac to dc resistance increase for several wire sizes are illustrated below:

$\frac{R_{AC}}{R_{DC}}$ calculates for AWG	#12 wire	1.211 a 21 percent increase
	#14 wire	1.076 a 7.6 percent increase
	#15 wire	1.032 a 3.2 percent increase

4.4.2 Inverter Losses

To reduce the skin effect losses the transformer design utilizes a number of parallel windings with smaller wire gages for the high current carrying primary winding.

A total of 12 paralleled AWG #14 windings are used for each primary half resulting in better coupling, lower winding resistance and increased efficiency.

The power conversion system is optimized for highest efficiency and minimum weight by the use of the plasma switches, transformer construction, rectification and the fault control system as well as the high voltage packaging layout.

Table 3 lists calculated individual components weight, losses and the resulting overall system efficiency and weight. Table 4 compares the system design goals with the calculated data.

TABLE 3. WEIGHT/LOSSES/EFFICIENCY

Component	Weight, kg	Losses, W
Core	15.0	880
Primary windings	1.8	1800
Secondary windings	2.0	1300
Rectifiers	23.0	3200
Hollotron and driver	9.3*	18300
Dielectric fluid	22.8	10
Hardware	2.3	
L.V. terminal	0.5	
H.V. terminal	1.5	
Insulation	5.6	
Housing	11.0	
Total	94.8	25490

Efficiency	97.5 percent

*From HRL

TABLE 4. 1 MEGAWATT T/R-HOLLOTRON UNIT DESIGN GOALS AND CALCULATED DESIGN DATA

Design Parameter	Design Goal	Calculated Design Data
Input voltage	5000 V dc	5000 V dc
Output voltage	100 kV at 10 A	100 kV at 10 A
Cycle to Cycle – voltage stability	±1.0 percent rms	≤ 1.0 percent rms
Frequency		20 kHz
Rectifiers		25 kV at 10 A/bridge 4 bridge/50 a surge
Size	Minimum (in cm)	XFMR = 41.9 x 31.7 x 21.6 RECT = 27.4 x 5.3 x 9.6 Hollotron = 8.4 x 18.8 OD
Weight	< 0.1 kg/kW	95 kg (0.095 kg/kW)
Flux density	—	5 k gauss
Total losses	—	25,490 watts
Efficiency	—	97.5 percent
Operating time	16 minutes	16 minutes
Ambient temperature	-40°C	-40°C

4.5 THERMAL ANALYSIS

Minimizing the transformer and component losses combined with a careful layout of heat generating and heat conducting components resulted in a relatively low temperature rise of the critical components. The transformer uses thermally conductive coil winding forms and incorporates heat conducting rods wound between the winding layers. The temperature profiles for the average and hot spot temperatures are shown in Figures 17 and 18. The highest hot spot coil temperature is 200°C and core temperature is 90°C. The average temperature for the coil and core are 175°C and 85°C respectively. These temperatures are well below the transformer insulation rating temperatures of 220+ degrees Celsius.

For the pulsed operation the temperature profile is shown in Figures 19 and 20 for the average and hot spot temperatures for the case of static cooling only. Figures 19 and 20 do not reflect the revised temperature profile calculations used for Figures 17 and 18 but are included to show the temperature increase trend for repetitive pulse operation. The pulsed operation requires longer cooling off periods or forced cooling to prevent the unit temperature from "ratcheting" up above the systems insulation rating.

4.6 RELIABILITY

The design of the converter was done with the primary consideration of high reliability minimum weight and highest efficiency. To maintain high reliability the design uses a minimum number of components. The converter components are designed for minimum electrical stress, minimizing particularly the ac stresses. The layout and packaging of the converter components are maintaining low voltage stresses to eliminate corona discharges. The construction of the components and their low electrical losses, minimize the converter temperature rise to a point lower than the temperature class rating of the insulation system. The fault control and driver circuitry increase the safety and reliability of the converter. The converter is meeting the goal limits of: 100 kg weight, 50 joules fault discharge, and 1 percent cycle to cycle regulation, while still maintaining the high system reliability.

4.7 CONCLUSIONS

The tradeoff studies resulted in an optimum transformer design, operating at 20 kHz, where the weight and losses are minimized, and in high system efficiency with lowest temperature rise. The calculated overall system weight goal of 100 kg is being met by this design.

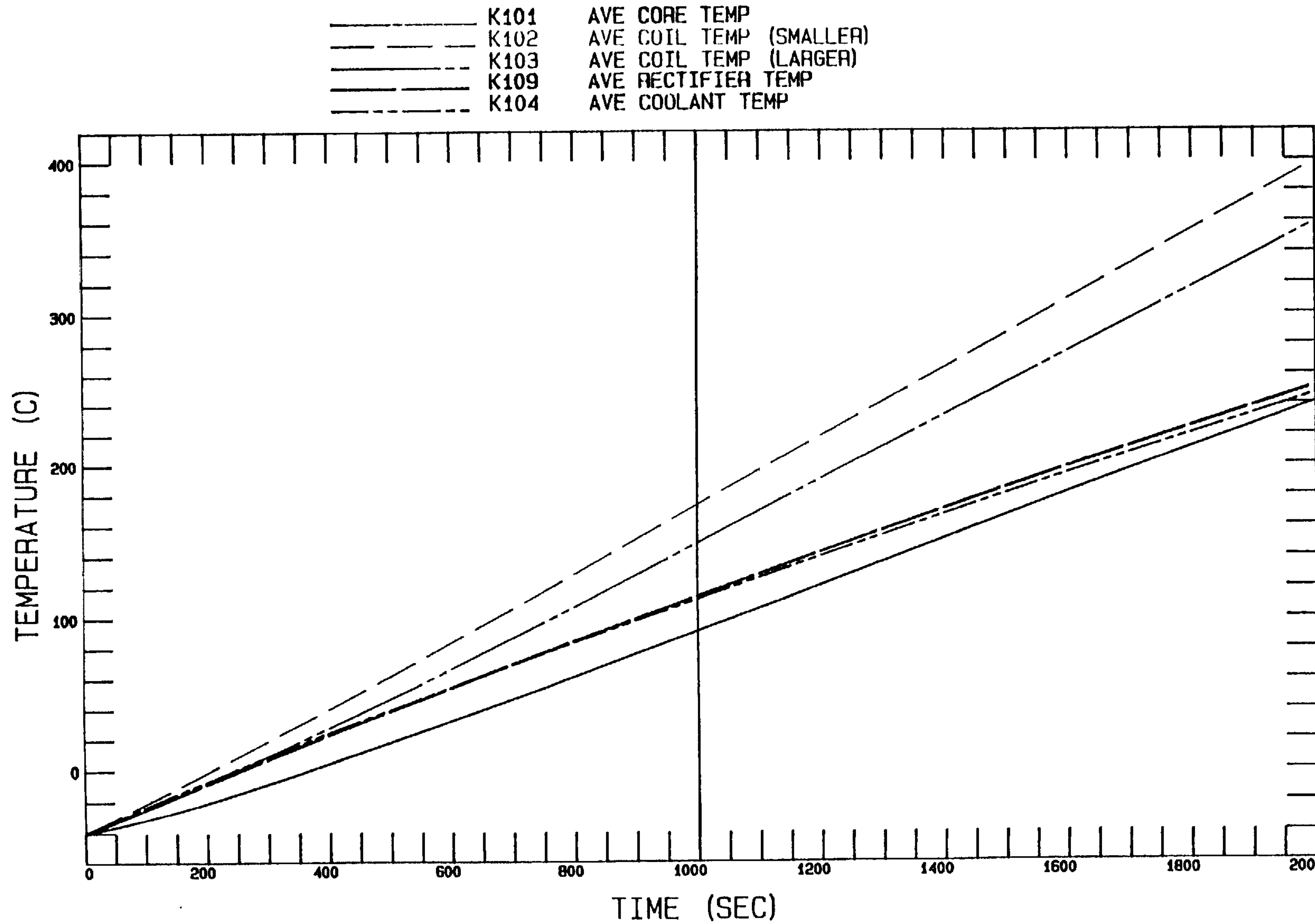


Figure 17. NASA transformer/rectifier unit static cooling, average temperatures.

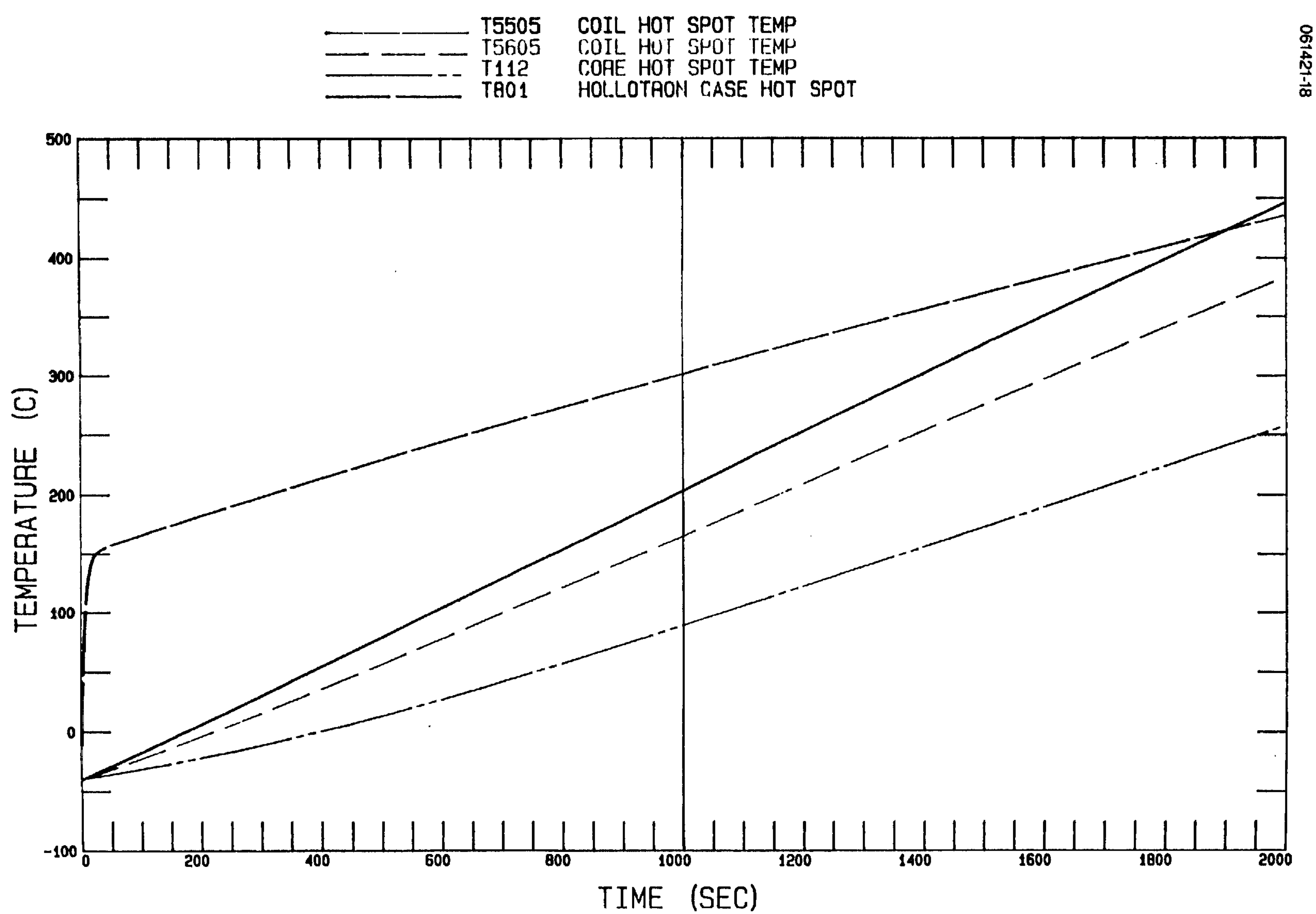


Figure 18. NASA transformer/rectifier unit static cooling, hot spot temperatures.

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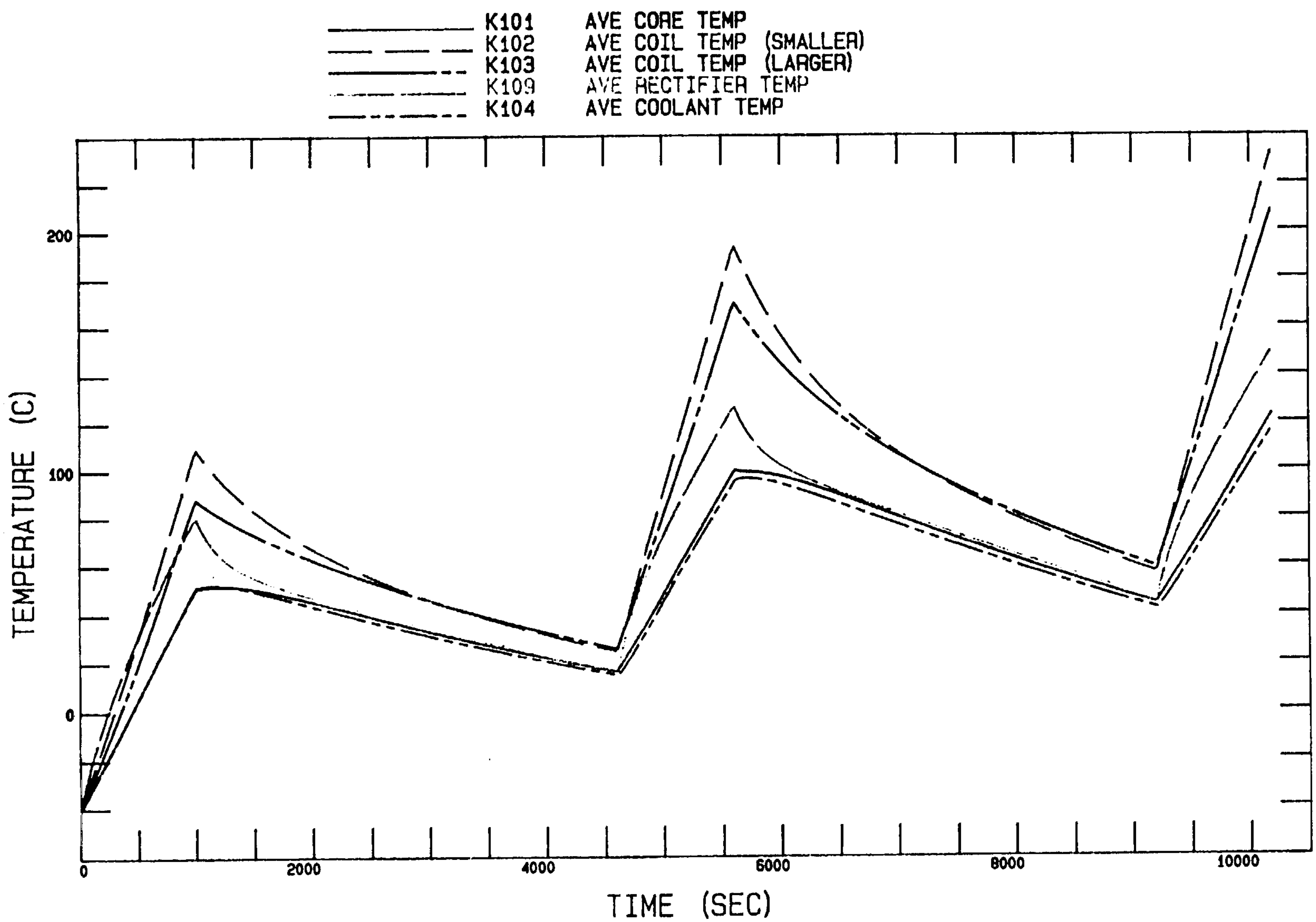


Figure 19. NASA transformer/rectifier unit pulsed operation, static cooling, average temperatures.

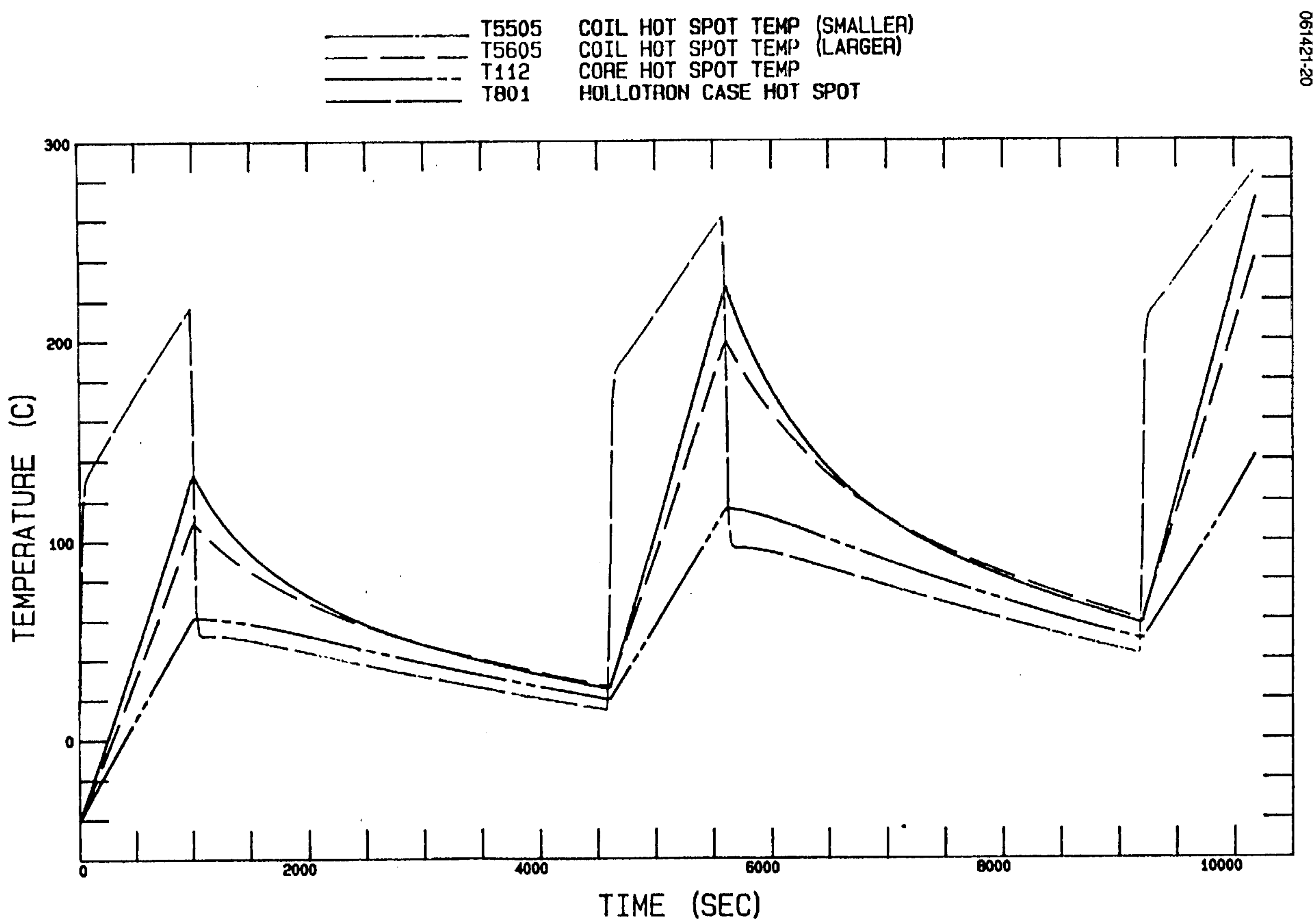


Figure 20. NASA transformer/rectifier unit pulsed operation, static cooling, hot spot temperatures.

5.0 PHASE II WORK PLAN

The Phase II program had been structured in three major tasks to be conducted in three consecutive years. In the first year a 50 kW breadboard dc to dc converter will be demonstrated; in the second year 1 MW Hollotron switches will be developed and 1 MW T/R components fabricated in parallel with development of a 1 MW package; in the third year two (2) 1 MW brassboard dc to dc converters will be fabricated, packaged and tested.

In Task I of the first year Phase II program, we will fabricate a 50 kW breadboard converter. The converter will consist of a full scale (1 MW size) transformer/rectifier with full size filter capacitors and a Hollotron switch driver. The Hollotron driver and housekeeping power will be external to the breadboard. The Hollotron switches will be rated at 10 amperes peak and 5 amperes average current but their envelope size will be full scale (1 MW size). The fault control circuitry will not be included on the 50 kW breadboard. However, the 50 kW power supply will be a variable 5 kV source with a fast overcurrent protection circuit (breaker) capable of shutting down the power supply within 5 milliseconds of an overcurrent condition.

The transformer-rectifier assembly will be in process tested at Hughes for dielectric withstanding voltage, low level turns ratio and basic transformer parameters. The uncased T/R assembly can also be tested in an oil bath at NASA with a 20 kHz sine wave input at the full 100 kV dc output voltage with no secondary load. It will also be tested at a lower ac sine wave input voltage for a 100 KW output delivering 10 kV dc into a 1 K ohm load (10A). Source and load to be provided by NASA or other location as available.

The 50 KW T/R – Hollotron prototype assembled as a broadboard (not encased) will also be tested at NASA (or NASA designated facility). The unit will be immersed in oil and driven from a 5 kV dc source. The output load will be 50 kW, 200 Kohm resistive. The source, load and all associated circuitry required for the converter testing will be supplied by NASA or a NASA designated facility.

For the second year of the program in Task II we will finalize and fabricate three sets of components for the full scale 1 MW converter to be used for the brassboard assemblies and one spare set of components. The full power Hollotron switches will be fabricated in the third year of the program, however one set of the 50 kW switches assembled into a full size 1 MW package will be available the second year for package development and component testing.

The components will be fully tested during fabrication and also in the 50 kW converter circuit. The packaging design will be refined and a mock-up package build. Thermal analysis will be performed based on the breadboard and brassboard components test results and a cooling scheme for the converter selected.

For the third year of the program we will fabricate and deliver two 1 MW dc to dc converter brassboards, fully assembled and encased plus 1 set of spare components. Each converter will consist of (2) full scale Hollotron switches, power transformer, (4) bridges, filter capacitors limited to 50 joules and 1 percent cycle to cycle output voltage variation, voltage divider network, fault control and Hollotron driver circuitry, high voltage and low voltage bushings, all encased in an oil filled metal container with bellows for oil expansion. The total weight of the converter will be under 100 Kg, and the efficiency of the 1 MW 100 kV dc output converter will be 97.5 percent or higher. At this time the housekeeping power supplies for the Hollotron control and fault circuitry will be in a separate package (not part of the converter weight), and will draw its power from the 60 Hz power line. The (2) brassboards will be tested at full power at a NASA designated facility, with NASA or the designated facility supplying the required input power, loads and all required test fixtures and measuring equipment. One set of spare components will also be delivered to NASA.

A final report and all required documentation will be supplied to NASA.

5.1 DC TO DC CONVERTER CIRCUIT

The schematic of Figure 1 shows the basic electrical circuit layout for the 1 MW, 5000 V dc to 100 kV dc converter.

The source is a fuel cell providing the 5000 V dc which is chopped at a 20 kHz rate by the two Hollotron switches S_1 and S_2. The transformer T1 steps up the 5000V, 20 kHz square wave of the primary winding to 25,000V in each of the four secondary windings. Each secondary rectifier bridge converts the induced secondary AC voltage to DC and charges its corresponding filter capacitor (C_1 thru C_4) to 25 kV dc. The rectified DC voltages are additively stacked up, by series connecting the secondary output capacitors to achieve the 100 kV dc total output voltage.

A resistive voltage divider R_2 and R_3 with balancing calibration capacitors (C_5 and C_6) are connected across the 100 kV dc output to provide a low level (10000 to 1) reference for monitoring the output voltage. Design calculations indicate that, as the total energy stored in the filter capacitors (C_1 to C_4) does not exceed 50 joules, the fault energy limiting resistor (R_1) can be omitted. The fault current limiting network (L1) can also be deleted as the current sense transformer (T_2) and the voltage sensing network of the fault control driver circuit response time is fast enough to shut off the Hollotron switches before an excessive primary fault current is reached.

5.2 CONTROL, FILTERING, AND FAULT PROTECTION

A control circuit will be designed for the Hollotron inverter to drive the Hollotrons, monitor the inverters operation, and shut it down under fault conditions. The output will be filtered to provide ±1 percent cycle-to-cycle voltage variation (ripple plus regulation) while limiting the energy delivered to the load under fault conditions to < 50 J.

5.2.1 Output Filtering

The inverter cannot be operated at 100 percent duty cycle because of the turn-ON and turn-OFF times of the Hollotron switches and the finite rise time of the transformer. These two characteristics will result in a gap in the flow of energy from the input to the output which will have to be filtered in order to meet the ±1 percent cycle-to-cycle voltage variation. A ±1 percent voltage variation at 100 kV represents a 2000 V peak-to-peak variation that can be tolerated. This variation will be almost entirely due to ripple on a cycle-to-cycle basis.

The deadband is due to both the switching times of the Hollotrons and the transformer rise time which are estimated to be 0.5 μs and 1.5 μs, respectively. This gives a gap in the energy flow of ~2.0 μs that needs to be filtered. Assuming a load current of 10 A and 2000 V of droop (allowed voltage variation), then from $C=IT/V$, the required total effective capacitance of the filter needs to be 0.01 μF or 0.04 μF (C1 through C4 of Figure 1) across each of the four rectified secondary windings. This capacitance will have a stored energy of 50 J at 100 kV which is the maximum allowed under fault conditions. Based on the above estimates, the fault current energy limiting resistor (R1 of Figure 1) may not be required and can be omitted.

5.2.2 Fault Protection

The output voltage will be sensed with a compensated voltage divider (R2, R3, C5, and C6 of Figure 1) and used to detect a load fault. This voltage will collapse very quickly under conditions of a load fault and should provide a faster means of detection than sensing load current. This signal will be used to turn both Hollotron switches OFF, shutting the inverter down. The response time of this loop is very critical, since the primary current of T1 will immediately start to increase when a load fault occurs. The increase in primary current will be limited mainly by the primary leakage inductance of T1 which has been calculated to be 25 μH. With a 5000 V source, this current will ramp at 200 A/μs resulting in a primary current (on top of the 200A load current) of 400 A in 1 μs. Since 400 A is the maximum current that the Hollotrons are expected to be able to interrupt, 1 μs is the maximum time after fault detection that can be allowed to turn the Hollotrons OFF. Further protection for the Hollotrons will be provided by sensing the primary current with T2 and using this signal to limit the switch current on a cycle by cycle basis. Preliminary estimates indicate that the two current sensing loops will be adequate to shut off the Hollotrons within the 1 μs response time, so that the L_1 network of Figure 1 may also be omitted.

5.2.3 Hollotron Drive Circuit

A pulse-width-modulator (PWM) integrated circuit will be used as the basic control for driving the Hollotrons. The UC3825 is a second generation PWM controller and its shutdown characteristics are considerably faster than the old UC1526; therefore, it is our preferred chip. It will provide the basic 20 kHz drive pulses for the push/pull primary and the dead time can be precisely controlled. The cycle by cycle current limit function is built into the chip as well as a shutdown function. The time responses on these functions are fast enough so that the extra inductor in the secondary may not be required.

5.2.4 Housekeeping Power

All housekeeping power for this inverter will be taken from 115 VAC, 60 Hz rather than from the 5000 V dc main bus power. This is being done to focus the effort on the main inverter rather than diverting part of it to developing housekeeping power from the 5000 V dc. In addition, we feel that it is reasonable to assume that in a real system, housekeeping power at a lower voltage will be available.

5.3 BREADBOARD 50 kW CONVERTER DEVELOPMENT (TASK 1)

A full size 1 MW T/R unit will be fabricated during the first year for the 50 kW breadboard demonstrator. Section 5.3 describes the transformer fabrication, transformer/rectifier assembly and integration, a description of the breadboard 50 kW Hollotron with full size development and breadboard testing.

5.3.1 Transformer Fabrication

The transformer design is essentially complete. For the winding of the coils, we will develop improvements in methods of maintaining precise wire lay and margins, anchoring the cooling rods, winding leads, layers of wire and insulation-without using adhesive tapes (in order to prevent gaps in impregnation which could cause corona breakdown). Also, the method of interconnecting and finishing the aluminum winding wires will be improved to minimize the voltage drops of the high winding currents. The transformer leads will be placed so as to minimize the voltage stresses and shorten their path to the corresponding interconnections - the switches at one end and the rectifier bridges at the other. The coil build up will be verified on the fabricated full size coil, to verify the actual core window size needed and the core will be ordered. The case enclosure will not yet be finalized at this time. In process testing of the coils will include turns count, DC resistance and leakage inductance. Placing a "dummy" core into the coil and vacuum impregnating the coil in a dielectric liquid, the coil winding capacitances and the Dielectric Withstanding Voltage (Hipot) of each secondary winding to core and primary will be tested. Each secondary winding will be exposed to a minimum Hipot of 130 percent of its nominal operating voltage. After both coil I and coil II are assembled to the actual core, the transformer will be tested for inductance, DCR, leakage inductance, self resonant frequency and voltage ratio at 20 kHz low level (50 V) sine wave.

5.3.2 Transformer/Rectifier Assembly

The rectifier stacks will be tested as received for a minimum of 40 kV dc peak inverse voltage. They will be assembled into bridge circuits and the bridges again tested for 40 kV peak inverse voltage.

The transformer and the four rectifier bridges will be interconnected and mounted together on a channel frame with the filter capacitors connected across the DC output of the bridges and series connected to achieve a DC total output equal to the sum of the individual secondary outputs. The T/R will then be tested at 50V 20 kHz sine wave input to verify the operation of the bridges, and the DC output of approximately 1000 volts. With the T/R submerged and impregnated in oil, the unit is capable of being tested at the full voltage level. The uncased T/R assembly will also be tested in an oil bath at NASA, or at a place specified by them, with a 20 kHz sine wave input at the full 100 kV dc output voltage with no secondary load. It will also be tested at a lower AC sine wave input voltage for a 100 KW output delivering a 10 kV dc into a 1 K ohm load (10 A). Source and load provided by NASA or as designated by them.

5.3.3 500 kW Hollotron Switch Approach Summary

The Hollotron switch design for the 1-MW power converter is based on the linear Hollotron switch, which was originally invented at Hughes Research Laboratories in 1989. The Hollotron switch for the 1-MW converter must close and open 200 A at 5 kV, with a pulse-repetition-frequency (PRF) of 20 kHz. The switch must also withstand 12-kV transients during normal operation and interrupt 400 A during faults. Under Hughes 1990 IR&D, we developed a new Hollotron switch which produced square pulses at 20-A peak current, at a maximum current density of 3.3 A/cm^2 and a voltage of 5 kV. The rise and fall times at the nominal 2 A/cm^2 were about 300 nsec. The interruptible current density as a function of the applied grid voltage is closely predicted by a simple theory developed for this switch geometry, which provides good confidence in scaling the switch to the final size.

For the Phase II program over the next year, a 50-kW demonstration unit will be built. This device will use the same switch as the final 1-MW converter, but requires that the switch interrupt only 10 A. The switch must still close 180 A to charge the stray capacitance in the transformer, and demonstrate the 300 nsec switching time at 20-kHz PRF and the 5 kV required for the final converter. Operation of the Hollotron switch in the 50 kW demonstration unit will provide an opportunity to optimize the switch performance for the final 1-MW operation in the second year.

During faults, the current can rise at a rate of 200 A/μsec. The fault current will be interrupted at a level of about 400 A, which corresponds to a current density of 3 A/cm^2. To ensure that the switch interrupts this current density, the control grid negative bias during interruption will be about 200 V. It is also possible to design the switch to limit the total current during faults without input current sense circuits. In this case, the current in the switch stalls at about 300 A due to insufficient plasma density in the gap between the control grid and anode. The voltage drop across the switch increases during the fault conditions, and the switch interrupts the current in a time of 1 to 2 μsec.

5.3.3.1 Phase II Hollotron Switch Specific Approach. In Phase II of the Ultralight MW Converter Program we will scale Xenon Hollotron switch performance to high peak (200-A) and average (100-A) currents at open-circuit voltage up to 18 kV. Our approach will be to employ the Hollotron configuration that was developed in 1990 under Hughes IR&D project entitled "Pulsed-Power Switches For Military Systems." Hollotron switch parameters are summarized below:

Maximum Anode Voltage	18 kV
Average Current	100 A
Maximum Interruptible Current	400 A
Control-Anode Gap Spacing	2 mm
Switching Time (10-90 percent on rise/fall)	300 ns
Forward Voltage Drop At 200 A	20 V
Mass	4.1 kg
Diameter	18.4 cm
Length	10.2 cm
Average Power	0.5 MW

The 0.5-MW average-power switch will be developed, integrated, and tested with the ultra-light MW inverter in a three-step, three-year program. A detailed schedule outlining the Phase II Hollotron development effort is presented in Figure 21.

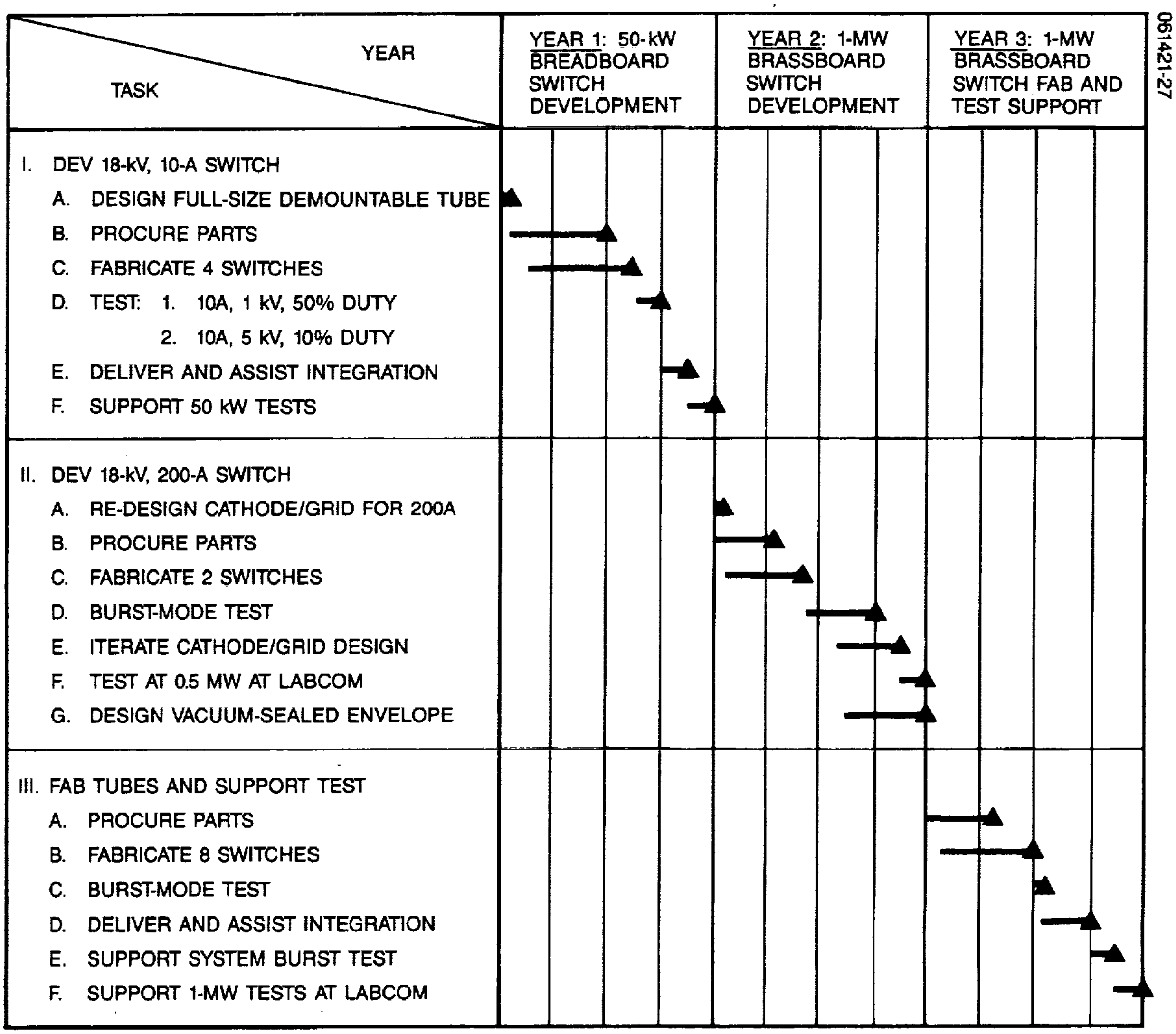


Figure 21. Hollotron inverter switch Phase II development schedule.

5.3.3.2 50 kW Breadboard Hollotron Switch Approach. In the first year we will develop a 50-kW breadboard inverter using full-sized, but not necessarily full-performance components. Hughes Research Laboratories (HRL) will develop a full-sized Hollotron switch for the breadboard circuit, but with reduced performance capabilities. The switch will be constructed with demountable vacuum flanges to facilitate performance optimization by easily iterating the configuration of internal components such as the cathode, magnet, and control grid. HRL will fabricate four switches in this first step, two tubes for the breadboard circuit, and two spare tubes. Prior to delivery to Hughes EDSG, the tubes will be tested at 5 kV, 10-A peak current, 20 kHz, and 10 percent duty (0.5-A average current). The switches will also be tested at full current (5-A average) and duty (50 percent), but reduced anode voltage. At the ninth month of the first year, the tubes will be delivered to EDSG and integrated into the breadboard circuit. Finally, HRL will support the 50-kW tests of the complete system at EDSG.

5.3.4 Breadboard Testing

The first Hollotron switches developed will be optimized for switching 10A. They will however be full scale switches packaged in full size envelopes. Using these switches, the prototype breadboard T/R will be tested at Hughes with 5000 VDC switched at a 20 kHz rate. The output voltage will be full 100 kV dc driven into a 50 KW 200K ohm resistive load. Also using the 5000 VDC source switched at 20 kHz rate without applying a load to the secondary, the core and dielectric losses will be established under square wave condition, for correlation with the ac sine wave measurements and the calculated losses.

The breadboard prototype converter can also be tested at NASA or NASA designated facility, with the test facility providing the power sources, loads and metering equipment.

The T/R assembly without the Hollotron switches and immersed in oil can be tested at the NASA facility at 20 kHz sine wave input with no secondary load and full 100 kV dc output voltage, and also at a reduced voltage at 20 kHz ac input with full secondary (10A) load current. At the 20 kHz sine wave with full primary voltage level applied, the ac excitation current and core losses will be measured. With the full secondary load current flowing thru the windings the I^2R losses of the windings and the voltage drops of the rectifier bridges will also be measured. The data will be used to verify the losses and for temperature rise calculation. If a 5000 VDC source of 50 kW or higher is available at NASA, the converter breadboard (including the Hollotron switches) can also be tested in a 20 kHz switching mode, similar to the test performed at Hughes - or, if the 5000 VDC source is not available, NASA representatives could witness the tests at the Hughes facility.

5.4 MEGAWATT COMPONENT AND PACKAGING DEVELOPMENT (TASK 2)

During the second year of the Phase II program the following work will be performed; 1) final drawings of the megawatt components, assembly and package, 2) megawatt component fabrication, 3) megawatt switch development, 4) packaging design and mock-up, and 5) thermal management.

5.4.1 Final Drawings

After the breadboard and component test results have been analyzed and any required changes to optimize the components performed, final drawings will be generated for the transformer, T/R assembly, T/R-Hollotron assembly and the control circuitry interconnection.

The fault control circuitry will be designed and developed during the second year of the Phase II program. The fault control circuitry termination and the primary current sense transformer integration will be incorporated into the drawings and process assembly instructions.

5.4.2 Megawatt Component Fabrication

Full scale 1 MW components for two brassboards and one spare set will be fabricated. They will include transformers, rectifiers, filter capacitors, voltage dividers, HV bushing and terminals, mounting brackets and insulators, bellows, and the enclosure.

The components will be tested during fabrication process, and also tested after being wired into a breadboard converter circuit at the full voltage 20 kHz switching mode. The tests will verify the components losses, wave shape parameters and high voltage withstanding ability.

5.4.3 Megawatt Switch Development

The second year of the program is aimed at the development of full power components. The peak current capability of the Hollotron switch will be extended to 200A by redesigning the hollow cathode, magnet, and grid assembly to handle the higher current. Specifically, we will increase the size of the cathode and the open area of the grid, and reduce the grid-aperture diameter. We will build two new demountable tubes using these new components and we will test the tubes at full voltage, but reduced current; full current, but reduced voltage; and both full voltage and current, but in a short burst of 20-kHz, 1-MW pulses. We will iterate the cathode/grid design based on these tests, and then test the tubes at full, simultaneous parameter values using the "CHIPS" 6.4-kV, 320-A test stand at the Army LABCOM pulsed-power facility at Fort Monmouth, New Jersey. By the end of the second year, we will have demonstrated the full 0.5-MW power modulating capability of the Xenon Hollotron switch in a simple square-wave, resistive-load circuit. As shown in the schedule in Figure 21, we will complete the design of a flangeless, vacuum-sealed envelope in parallel with the switch tests.

5.4.4 Packaging Enclosure Design and Mockup

A mock-up enclosure package will be generated, using the drawings of the full component sizes, to aid in developing the brassboard packaging. The brassboard packaging layout will thus be generated to scale, packaging details finalized and all packaging drawings generated.

5.4.5 Thermal Management

The results of testing the prototype transformer, rectifiers and switches will be used to calculate and verify the converter losses and perform an accurate thermal analysis of the T/R-Hollotron assembly. The thermal analysis will indicate the operating temperature range of the system, the expansion range needed for the bellows, and the highest temperature the components will reach under single power pulse, and repeated continuous pulse power operation. Preliminary calculations indicate that under single power pulse operation with long power-off intervals, the system, even with static cooling only, maintains a safe maximum components operating temperature, considerably lower than the temperature class rating of the components.

For operating the system under repeated 16 minutes 1 MW power pulses with only 1 hour power off intervals, the system will require forced oil cooling. For that purpose a recirculating high efficiency, light weight heat exchanger will be required. The heat exchanger pump will be external to the converter assembly. The required flow rate of the cooling oil will be established by thermal analysis. Figure 22 shows the converter cooling schemes. The pump is estimated to weigh 4.5 kg with 1 kg for the heat exchanger and 0.5 kg for the hardware piping. Active cooling will add an estimated 6 kg to the total converter weight.

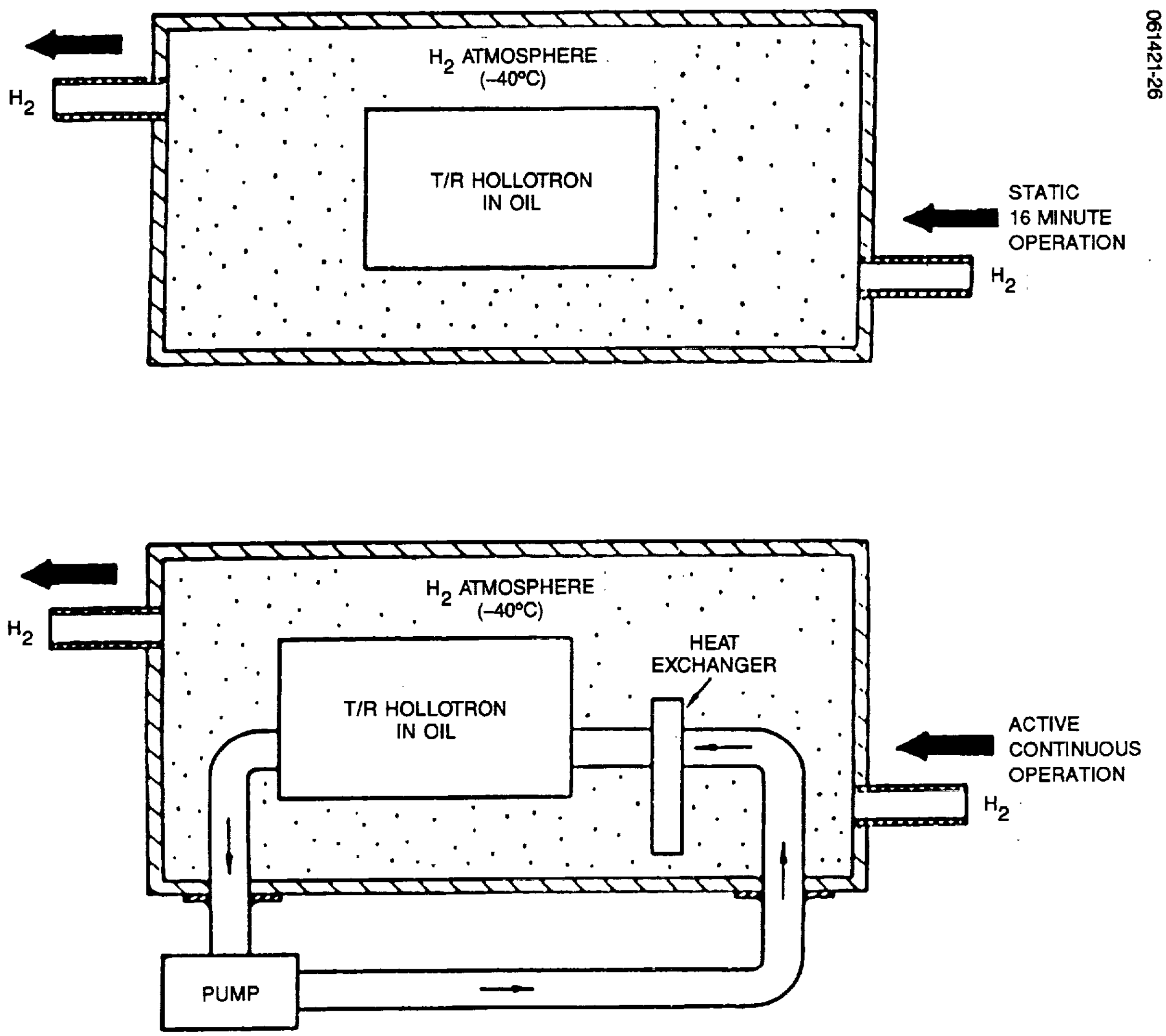


Figure 22. Preliminary cooling schemes.

5.5 BRASSBOARD FABRICATION PACKAGING AND TESTING (TASK 3)

During the third year of the Phase II program the following work will be performed:

1. (8) full scale Hollotron switches will be fabricated.
2. (2) brassboard converter enclosures including all hardware will be fabricated.
3. (2) brassboards, 1 MW converters will be assembled.
4. (2) brassboard converters and one set of spare components will be tested and delivered to NASA.
5. Final report will be generated.

5.5.1 Megawatt Hollotron Switch Fabrication/Test

In the third year of the program we will exploit the full-performance design to manufacture eight prototype 0.5-MW Hollotron switches for the two brassboard inverter circuits. Four tubes will be used in the brassboards, and four tubes will be available as spares. At six months into the third year, the first tubes will be completed, and they will be tested in the same manner as that used in the second year—reduced-power and short-burst evaluations. The tubes will be integrated into the brassboard circuits and short-burst, full-power tests of both circuits will be done at EDSG. Finally, both brassboard circuits will be shipped for full-power, full 16-minute-burst tests at the Army LABCOM facility. HRL will support these tests with engineering personnel to assure full switch performance.

Following the completion of full-power brassboard inverter tests, HRL will assist EDSG in the preparation of a final report.

5.5.2 Full Brassboard Packaging

The 1 Megawatt DC to DC converter will be assembled into the package fabricated from the mock-up enclosure and drawings developed during the second year of the program. The enclosure consists of an oil filled metal container with bellows to allow for oil expansion/contraction over the operating temperature range. The input ceramic terminals as well as the low voltage power and control terminals will be at the "Low" voltage end of the enclosure. The flat 100 kV output terminal bushing shown in Figure 23 will be at the opposite (High Voltage) end of the container. The bottom end of the container will have reinforcement channels to support the weight of the components.

The internal package layout indicated in Figures 24, 25 and 26 show the sequential buildup of the voltages within the assembly. Thus at one end the highest stress is 5 kV to ground at the Hollotron switches and primary transformer side (10 kV across the total primary), 25 kV in the center section at the secondary outputs, and 100 kV dc at the output bushing after the rectification and series connection of the rectified secondary output voltages. As the voltage within the assembly increases, the spacing and the radii of the conductors are correspondingly increased to maintain the electrical stresses within safe limits of the insulation system.

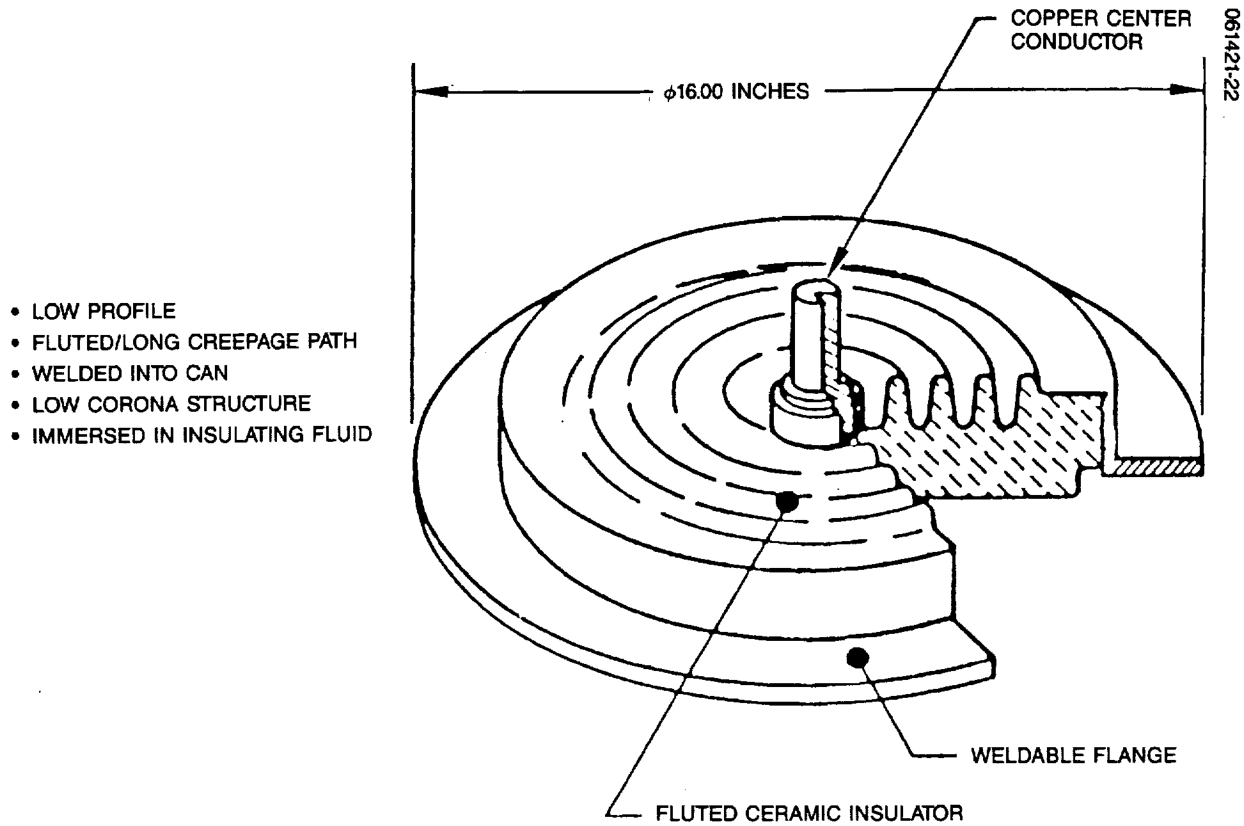


Figure 23. High voltage output terminal.

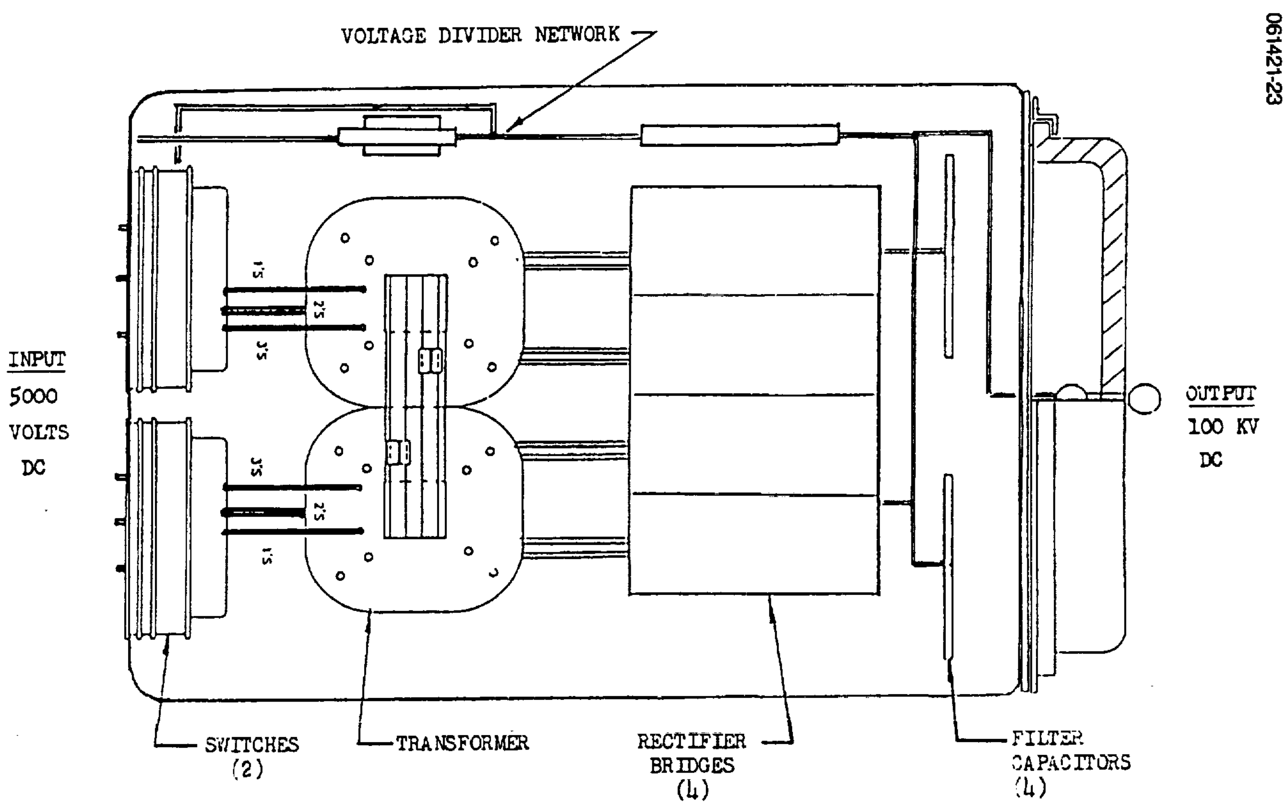
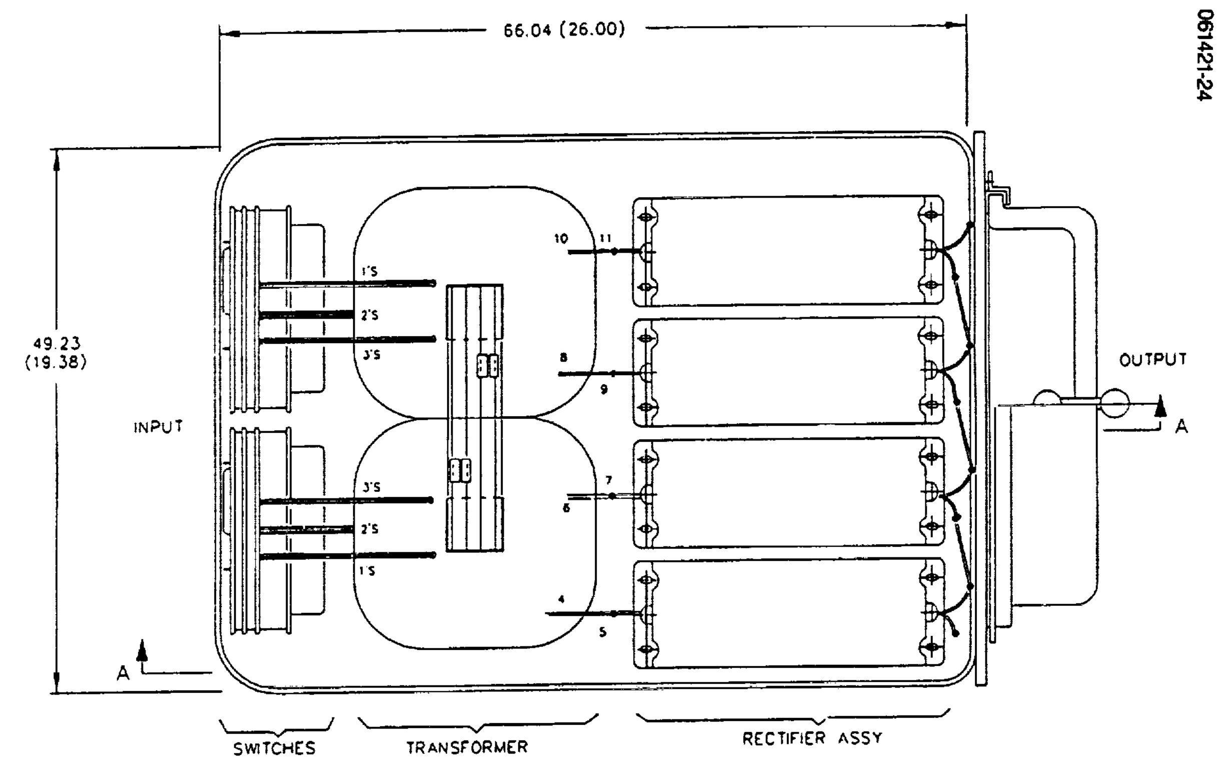
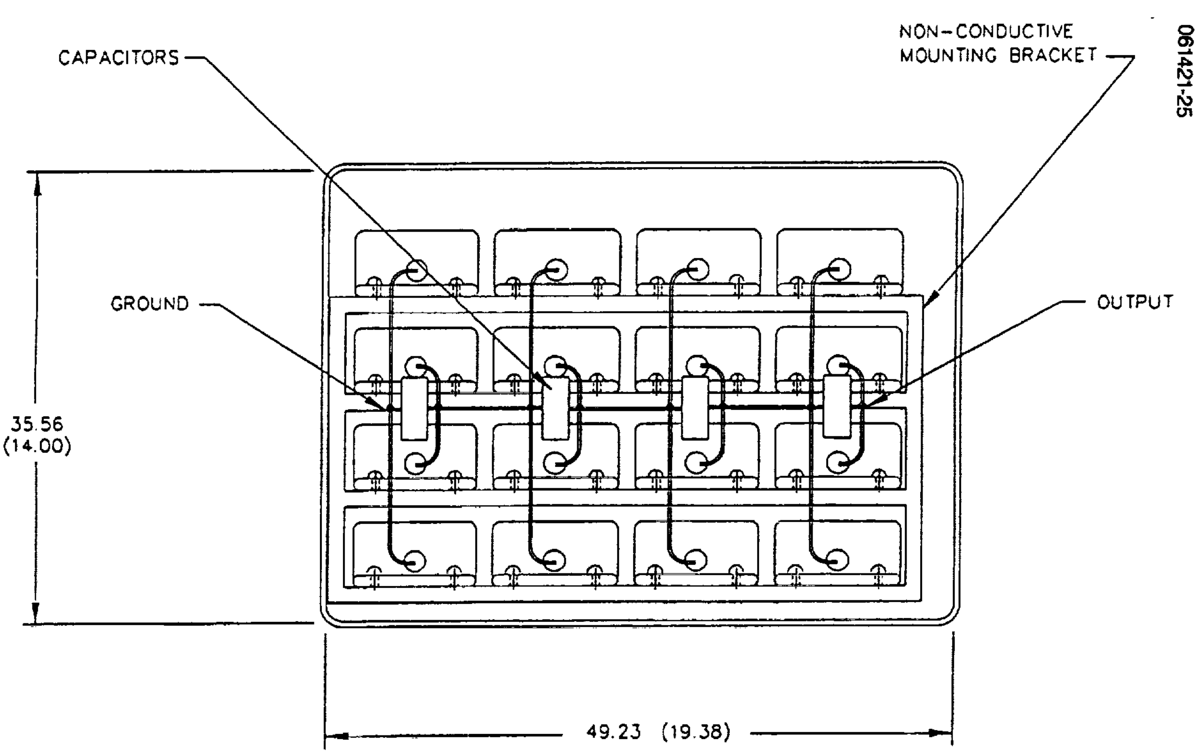


Figure 24. Power supply assembly — top view packaging concept.



DIMENSIONS IN CENTIMETERS (INCHES)

Figure 25. Inverter assembly — top view.



DIMENSIONS IN CENTIMETERS (INCHES)

Figure 26. Inverter assembly — rear view.

The enclosure will also have a filling plug through which the air will be evacuated and the oil dielectric introduced into the container, thus eliminating corona causing voids. During vacuum filling the bellows will be held at an appropriate intermediate height expansion corresponding to the temperature of the oil to allow sufficient bellows range for expansion and contraction over the expected converter operating temperature range.

5.5.3 Brassboards Fabrication

Two full scale 1 MW brassboards converters including one set of spare full scale Hollotron switches will be fabricated. Each converter will consist of two full scale Hollotron switches, power transformer, four High Voltage rectifier bridges, four 0.04 µf-25 kV filter capacitors, a 10000 to 1 voltage divider network, Hollotron driver, primary current sense transformer and fault control circuitry.

The Hollotrons, transformer, rectifiers, filter capacitors, current transformer and the voltage divider network will be assembled into a lightweight metal enclosure. A specially designed High Voltage fluted flat construction ceramic bushing shown in Figure 23 will provide the 100 kV dc output termination. The bushing is rated for 150 kV dc in air. The converter enclosure will be filled with silicate ester fluid and will have bellows to provide for the oil expansion and contraction.

The components will be in process tested for dielectric withstanding voltage and low power level operation before and after assembly into the converter circuit. The converter assembled into the enclosure will be vacuum filled with the dielectric insulating fluid (silicate ester) and the filling plug sealed. The bellows will be extended to their proper position and have sufficient extension range to allow for the oil expansion and contraction over the entire operating temperature range. The Hollotron driver and fault control circuitry as well as the "housekeeping" power supplies for the control circuits will be external to the converter assembly.

5.5.4 Brassboard Testing

In addition to in process testing of the converter components during fabrication, each brassboard converter will be tested at Hughes in the 20 kHz switching mode with 5000 VDC input and the 100 kV dc output loaded with a 50 kW resistive load. The fault control circuit will also be tested using a crowbar switch across the load to simulate an arc (short). Hughes will also test the brassboards with short bursts (0.5 milliseconds or higher) of full 1 MW power pulses. For that purpose the converters will be loaded resistively with a 10 kilo ohm load, and a 5 kV dc capacitor bank of about 200 µF will be discharged into the converter input to provide a minimum of a 10 cycle power burst. At the Army LABCOM or a NASA designated facility the brassboard converters will be tested at full 100 kV dc output voltage with a 1 MW resistive load. The fault control circuit may also be tested at NASA with high voltage fault simulation switches provided by NASA.

A final report will be generated and delivered to NASA will all fabrication and test documentation.

6.0 PROGRAM SCHEDULE

The three year Phase II program will be conducted according to the milestones and schedule in Figure 27. A 50 kW breadboard will be delivered at the end of the first year and two 1 MW brassboard dc to dc converters will be delivered at the end of the third year.

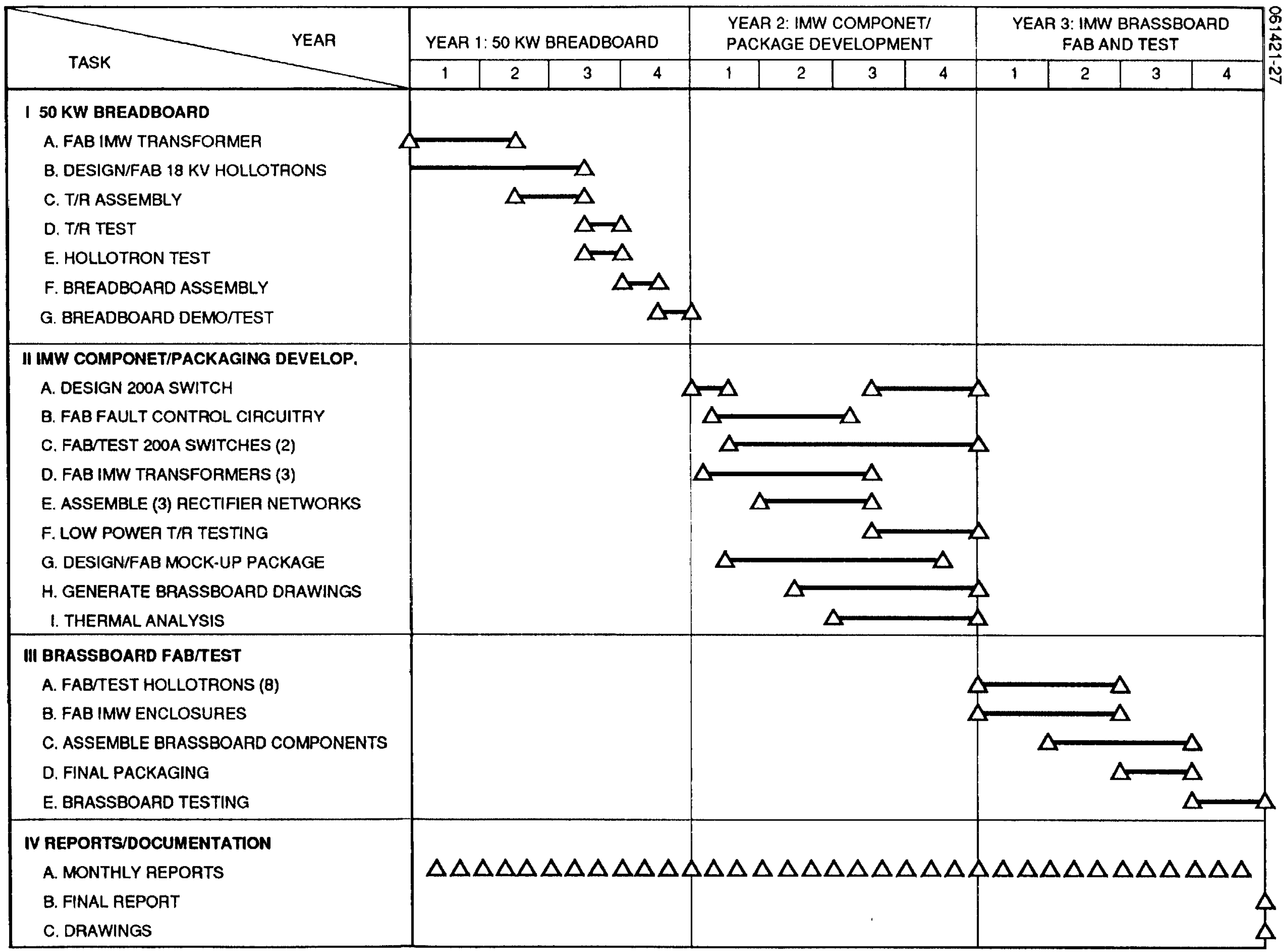


Figure 27. Program schedule.

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16. Abstract
The goal of the two phase program is to develop the technology and design and fabricate ultralightweight high reliability DC to DC converters for space power application. The converters will operate from a 5000 V dc source and deliver 1 MW of power at 100 kV dc. The power weight density goal is 0.1 kg/kW. The cycle to cycle voltage stability goal was ±1 percent RMS. The converter is to operate at an ambient temperature of -40°C with 16 minute power pulses and one hour off time. The uniqueness of our design approach Phase I resided in the dc switching array which operates the converter at 20 kHz using unique Hollotron plasma switches along with a specially designed low loss, low leakage inductance and a lightweight high voltage transformer. This approach reduced considerably the number of components in the converter thereby increasing the system reliability. To achieve an optimum transformer for this application, the design uses four 25 kV secondary windings to produce the 100 kV dc output, thus reducing the transformer leakage inductance, and the ac voltage stresses. A specially designed insulation system improves the high voltage dielectric withstanding ability and reduces the insulation path thickness thereby reducing the component weight. Tradeoff studies and tests conducted on scaled-down model circuits and using representative coil insulation paths have verified the calculated transformer wave shape parameters and the insulation system safety. In Phase I of the program a converter design approach was developed and a preliminary transformer design was completed. A fault control circuit was designed and a thermal profile of the converter was also developed. The converter design exceeds all the program goals including the following: less than 1 percent cycle to cycle voltage stability, a power weight density of 0.095 kg/kW and a fault tolerance energy of less than 50 joules. For Phase II of the program in the first year a 50 kW breadboard converter will be fabricated and tested. The converter will include Hollotron switches that are capable of switching 10 A at 5000 V with less than 20 V forward drop, but will be packaged into 1 MW full size switch envelopes to aid in converter packaging development. The transformer and rectifiers will also be full voltage and power size. During the second year of Phase II all the full megawatt size components will be developed, fabricated and tested. The development of the full MW size Hollotron switches will also be started during the second year as well as the packaging design. During the third year of the Phase II program full 1 MW power switches will be fabricated, and 2 brassboard converters fully integrated and packaged into oil filled enclosures will be tested and delivered.

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